Appendix A LITERATURE REVIEW

Pacific Environment Limited

Consulting • Technologies • Monitoring • Toxicology

Report

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

Literature review

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CONTENTS

1 INTRODUCTION

Pacific Environment has been commissioned by NSW Roads and Maritime Services (RMS) to undertake a study entitled *Road tunnels: Reductions in nitrogen dioxide (NO_2) concentrations in-cabin using vehicle ventilation systems*. The study will involve detailed measurements of NO_2 concentrations inside cars that are being driven through road tunnels in Sydney, as well as the development and validation of in-vehicle pollution models. The outcomes of the study will be used to inform the design and operation of future road tunnels in Australia.

1.1.1 Background to the study

A number of major road infrastructure developments are currently planned for Sydney, and tunnels feature prominently amongst these - notably in the NorthConnex and WestConnex projects. If it is approved, WestConnex will form the longest road tunnel network in Australia. As air quality has historically been a factor that influences the acceptance of road tunnels by the Sydney community, research in this area is required. The concerns of the community have tended to focus on ambient air quality and the effects of tunnel ventilation stacks. However, given the length of the planned tunnels for NorthConnex and WestConnex, and the likely volumes of traffic in the tunnels, the potential exposure of vehicle occupants to elevated in-tunnel pollutant concentrations is subject to an increasing level of scrutiny.

In many tunnels the demand for fresh air (*i.e.* ventilation sizing) to reduce in-tunnel pollutant concentrations is calculated according to guidelines from the World Road Association (PIARC). The fresh air requirements for tunnel ventilation design and control have traditionally been based upon the in-tunnel concentration of carbon monoxide (CO). In the past, most of the CO was emitted by petrol-engined 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 increased market penetration of diesel vehicles in passenger car fleets (more so in Europe than in Australia to date) has meant that some countries are now considering the use of nitrogen dioxide (NO_2) concentrations for tunnel ventilation sizing. This shift is further supported by evidence (again, mainly from the UK) of the increase in primary NO_2 emissions from road vehicles.

For the planned tunnels in Sydney it is likely that ventilation sizing will be dictated by in-tunnel NO_2 concentrations rather than ambient air quality considerations, and the use of correct assumptions for in-tunnel exposure will therefore be vital. However, there is little evidence in the literature relating to the success or otherwise of in-tunnel NO_2 limits, other than general comments to the effect that the management of NO_2 will require the development of reliable monitoring methods and models for in-tunnel concentrations. The exposure of vehicle occupants to NO_2 in tunnels, and the implications of this for tunnel ventilation design, have not been studied in detail. Whilst this is considered in some overseas guidance, such as the the UK Design Manual for Roads and Bridges **(Highways Agency *et al.*, 1999)**, it is not explicitly addressed by PIARC or other Australian guidance.

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

> *'...research, develop and make recommendations on in-tunnel NO_2 limits that would provide an appropriate level of protection in the medium to long term.'*

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

The Committee has set up a Working Group to collate information on the air exchange rate (AER) of passenger vehicles and the effectiveness of vehicle ventilation systems in reducing occupant exposure to NO_2 in road tunnels in Sydney.

This study has been established by RMS to obtain primary data on exposure to NO_2. The exposure of vehicle occupants to NO_2 in tunnels will be strongly dependent upon the capacity of the vehicle's ventilation system to minimise the AER. The study therefore deals with both AERs and in-vehicle NO_2.

1.1.2 Objectives

The objectives of the study are as follows:

1. To quantify the AERs and in-vehicle NO_2 concentrations for passenger vehicles (cars only) being driven through road tunnels in Sydney. The vehicles will reflect the types and ages of the current and future passenger vehicle fleet.

2. To compare NO_2 concentrations inside vehicles with those outside vehicles in the tunnel air, and subsequently determine inside-to-outside (I/O) ratios for NO_2.

3. To understand the influence of vehicle ventilation settings and other parameters on in-vehicle NO_2 concentrations.

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-tunnel NO_2 concentrations and in-vehicle NO_2 concentrations.

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

- In-tunnel pollutant NO_2 concentration profiles (concentration as a function of distance into the tunnel). To date, mobile monitoring methods have not been used to give high-resolution NO_2 concentration profiles inside tunnels.

- Driving patterns in Sydney for both surface roads and tunnel roads. It will be of interest to see, for example, how speed variation[b] compares for surface roads and tunnel roads.

1.1.3 Purpose of literature review and gap analysis

This Report is the first deliverable from the project, and contains the following:

- A literature review which identifies the main factors influencing AERs and in-vehicle pollutant concentrations, and summarises models that have been developed to characterise these (**Chapter 2**).

- A review of suitable measurement methods for CO_2 (for determining AERs) and NO_2 (**Chapter 3**).

- A review of road tunnels in Sydney (**Chapter 4**).

- A description of the Sydney car fleet (**Chapter 5**).

[b] Emissions from road vehicles are usually stated as a function of average trip speed. However, the amount of variation in speed during a trip (<u>for a given average speed</u>) is an important determinant of emissions. Statistical measures such as absolute positive acceleration (APA) or relative positive acceleration (RPA) can be used to describe this variation in speed.

- A gap analysis (**Chapter 5**).
- References (**Chapter 7**).

2 LITERATURE REVIEW

2.1 Background

This chapter of the report presents the findings of the literature review.

Many studies in the scientific literature, dating back some 50 years, have described measurements of in-vehicle pollutant exposure. By comparison, few studies have linked on-road and in-vehicle pollution through measurements of I/O concentration ratios. Even fewer studies have focussed on pollutant concentrations inside vehicles being driven through tunnels. Moreover, much of the earlier work has dealt with CO rather than NO_2.

The chapter describes the central role of the vehicle air exchange rate (AER) in determining the relationship between pollutant concentrations inside and outside a vehicle, and the factors affecting this relationship. It also summarises the models that have been developed to predict in-vehicle exposure.

2.1.1 Air exchange rate

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, and is also referred to in some literature as air changes per hour (ACH). The incoming air displaces (*i.e.* exchanges) an equivalent volume of in-cabin air and this is represented schematically in **Figure 2-1**.

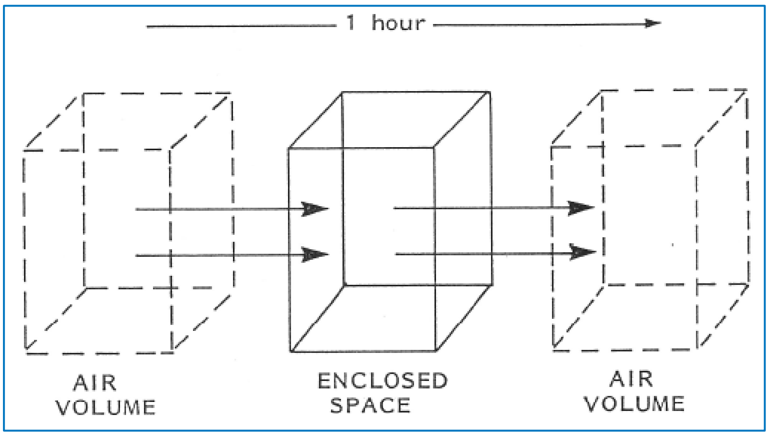


Figure 2-1: Schematic representation of 1 ACH (Charlesworth, 1988)

During both mobile and stationary vehicle operation the exchange of air occurs between the vehicle cabin and the outside environment through leaks in the body of the vehicle (door seals, window cracks, *etc.*) and through the ventilation system when it is set to draw air into the cabin.

The AER has been shown to be a key determinant of in-vehicle exposure to traffic pollutants, including Particle Number Concentrations (PNC) **(Goel and Kumar 2015)**, and thus the AER controls how much on-road pollution is able to reach the cabin **(*e.g.* Knibbs *et al.*, 2010)**. It is therefore important to have high quality measurements in order to understand the relationship between pollutant levels in these two locations.

While the AER is one of the main factors affecting on-road to in-cabin pollutant transport, it is affected in turn by several parameters. These include the size and distribution of air leakage sites, pressure differences induced by wind and temperature, mechanical ventilation system settings, occupant behaviour and vehicle speed **(Fletcher and Saunders, 1994)**.

2.1.2 I/O ratios

The inside-to-outside ratio (I/O) of pollutants represent the ratio of the concentrations of in-vehicle pollutants to the concentration of outside-air pollutants. There has found to be a close correspondence between I/O ratio and AER (R^2 = 0.75 - 0.81), and this is dependent upon on the in-vehicle ventilation settings **(Knibbs *et al*., 2010; Hudda *et al*., 2011)**. At relatively polluted locations, such as on busy urban roads or in road tunnels, air continually replenishes in the vehicle cabin with pollutants from the outside environment. Under such circumstances a lower AER would be desirable and air-recirculation mode has been shown to be preferable when driving in congested urban traffic **(Chan and Chung, 2003)**. If ambient concentrations of a pollutant are low but for some reason the levels are increasing inside a vehicle, a high AER is desirable **(Chan, 2003)**.

The AER and I/O ratio are dependent, in turn, upon vehicle age (or model year), country of manufacture, vehicle speed and fan strength **(Knibbs *et al*., 2009; Hudda *et al*., 2011; Hudda *et al*., 2012)**. These factors are discussed below in greater detail.

2.2 Influencing factors

2.2.1 Vehicle age/model year

In early investigations the average I/O ratio for CO during normal driving on open roads was found to range from 0.3 **(Hickman and Hughes, 1978)**, up to 1.6 **(Chan *et al*., 2002)**; however, the majority of studies found that the ratio was close to unity **(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)**. Ratios close to unity were also observed for VOCs and NO_2 **(Febo and Perrino, 1995)**. These findings suggest that old vehicles had high AERs and were quite 'leaky', leading to concentrations of pollutants in vehicles were at similar levels to on-road air pollution.

Modern vehicles generally have significantly lower AERs due to improved filters, and have the potential to be an inexpensive solution to reduce human exposure to vehicle pollution **(Pui *et al*., 2008)**. **Knibbs *et al*. (2009)** measured I/O ratios for a range of vehicles driving through tunnels in Sydney; the lowest I/O ratios were found for modern post-2005 vehicles under recirculation (RC) conditions and a low fan speed. However, I/O ratios were overall similar for post-2005 cars (0.08 – 0.68), and older models from 1989 and 1998 (0.29 – 0.47). The I/O ratios were high for models of all age under outside air intake (OA) conditions (0.89 – 1.04), except for the filter-fitted 2005 VW Golf. Therefore, advances in vehicle air filters would be expected to reduce I/O ratios in the future. Air filters in modern cars have also been shown to slightly reduce in-cabin UFP concentrations **(Pui *et al*., 2008; Qi *et al*., 2008)**.

Hudda *et al*. (2011) found that the AER increased with speed for older vehicles under OA conditions; however, this did not have a significant effect on the I/O ratio. Under RC conditions, AER and I/O ratios were strongly correlated with vehicle speed – regardless of vehicle age. A further discussion of the effects of vehicle speed is given in the following section.

2.2.2 Vehicle manufacturer

The vehicle manufacturer (or country of origin) has a demonstrated effect on the AER due to the quality of manufacturing. Higher quality vehicles are expected to have lower AERs and lower I/O ratios. For example, the model developed by **Hudda *et al*. (2012)** has separate 'manufacturer adjustments' for country of origin. Other things being equal, a vehicle manufactured in the US is expected to have an AER that is nearly 50% higher than a Japanese vehicle and about twice as high as a vehicle manufactured in Germany. The test vehicles will therefore include, as far as possible, vehicles originating from different countries.

2.2.3 Vehicle speed

Vehicle speed also affects the AER and I/O ratio, whereby faster speeds for vehicles of varying ages have been shown to lead to greater AERs and higher I/O ratios, suggesting that pressure differences between out-of-vehicle and in-vehicle air, as well as outside air turbulence, impact the rate at which air enters a vehicle **(Fruin et al., 2011; Ott *et al.*, 2008; Knibbs et al., 2009)**.

Under RC conditions and driving at a speed of 60 km/h, **Fruin *et al.* (2011) and Knibbs et al. (2009)** determined that the number of air changes per hour was 1.0 for the most airtight vehicle, and 33.1 for the least airtight vehicle. Increasing the speed to 110 km/h increased the number of air exchanges per hour to 2.6 and 47.1 for the most airtight vehicle and least airtight vehicle, respectively. Thus the AER is higher for less airtight (old) vehicles even under low speeds, and more airtight (modern) vehicles have lower AERs, even under high speeds.

2.2.4 Vehicle ventilation settings

Vehicles are generally designed to provide two different types of ventilation inside the cabin. The OA setting allows for air to be sourced from outside the vehicle and replenish the in-vehicle air. Under this setting, air from the outside is able to flow into the vehicle before being exhausted through an area at the front of the vehicle. Alternatively, when the RC setting is chosen the outside air entry point is sealed and pre-existing air from within the cabin is recirculated with the assistance of a fan. Evidently this will have a large impact on the AER and I/O ratio. In addition, the ventilation fan speed affects these parameters and this is also discussed in this section.

A study in Hong Kong showed that when driving around high-pollution environments under OA conditions, pollutant concentrations generally reflect outside air concentrations **(Chan and Chung, 2003)**. This can lead to in-vehicle pollutants concentrations of 0.3 and 2.5 ppm for NO_x and CO, respectively, which is close to the limits recommended by the World Health Organization. In contrast, under RC conditions in-vehicle NO_x concentrations showed no relationship with outside concentration levels; however, CO did show a strong relationship with outside concentration levels (R^2 = 0.80 vs 0.22), suggesting that CO may be prone to in-vehicle penetration than NO_x. As discussed previously, **Knibbs *et al.* (2009)** found that air changes per hour and I/O ratios were much lower under RC conditions compared to under OA conditions.

In addition to RC or OA settings, the fan speed can also affect in-vehicle concentrations of CO and NO_x. **Knibbs *et al.* (2009)** showed that higher fan speeds under RC conditions decreased the 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 under AC conditions, which is likely due to more air and therefore more pollutants being cycled into the vehicle.

2.3 In-tunnel studies

Studies have shown that in-vehicle pollutant concentrations are significantly higher whilst driving through tunnels compared with driving on surface roads **(Löfgren *et al.*, 1991; Barrefors and Petersson, 1992; Lawryk and Weisel, 1996)**. A study performed to determine the influence of traffic intersections on PNCs concluded that in-cabin PNCs increased during congestion at intersections, particularly in built up areas where there was little opportunity for pollutants to disperse **(Goel and Kumar, 2015)**. The study highlights potentially the largest cause of pollutants concentration increases in tunnels- the inability of pollutants to disperse. Uncertainties however still remain regarding how the concentration of pollutants varies with the distance into a tunnel, and how this affects I/O ratios of pollutants.

NO_2 was one of the pollutants included in 2003 study in Sydney's M5 East tunnel for NSW Department of Health **(Cains *et al.*, 2003)**. However, in-vehicle and in-tunnel air concentrations were measured using passive samplers, resulting in a limited temporal resolution (only one measurement was obtained per day). More recently, **Knibbs *et al.*, (2010)** showed that in-vehicle concentrations of ultrafine particles

(UFP) were much higher in tunnels compared to surface roads in Sydney. Thus exposure of humans to in-vehicle pollutants from travelling in tunnels could significantly contribute to total daily exposure levels.

Distance into the tunnel appears to be linearly correlated with in-vehicle pollutant concentrations both inside and outside the vehicle. **Chan and Chung (2003)** showed that high concentrations of CO and NO_x were found at the tunnel exit where concentrations were typically 30% higher than the entrance. This was attributed to the installation of a jet fan which pumps air through the tunnel towards the exit. Additionally, **Gouriou et al. (2004)** found that PM concentrations were approximately six times higher at tunnel exits compared to tunnel entrances. The highest PM concentrations corresponded to size class distributions from diesel fuel emissions. Decreased air pollutant concentrations at the entrance may potentially be due to a piston effect whereby fresh air is dragged into the tunnels by cars. **Chan and Chung (2003)** determined that the rise in in-vehicle pollutant concentrations in a tunnel was fastest under OA settings with NO concentrations peaking in-cabin approximately 2 minutes after an outdoor peak in NO concentrations was observed. This in-vehicle peak was determined to reach approximately 95% of the outdoor concentration but dropped quite rapidly under OA settings. In contrast, NO_2 levels appeared to accumulate and build up more slowly in tunnels with peak indoor NO_2 concentrations reaching slightly above the peak outdoor concentrations. These findings suggest that the I/O ratio of NO_2 would likely be highest under RC conditions at the tunnel exit under low speeds, as this would allow time for NO_2 concentrations to build up within the vehicle. These high concentrations can be rapidly reduced using the OA setting (or opening windows) which allows for greater throughput of air and dilution effects.

In summary, it therefore would appear that the greatest contributing factors to outside air concentrations of NO, NO_2 and CO in tunnels is the distance into the tunnel (with pollutant levels inside the vehicle dropping at the tunnel entrance and then peaking after exiting the tunnel under RC ventilation conditions). Pollution levels in tunnels will also be related to the degree of traffic congestion and associated time spent in the tunnel, with high concentrations in heavy traffic. In-vehicle ventilation settings (RC or OA) have also been shown to be key controls on in-vehicle pollutant build up whilst driving through tunnels. Since air changes per hour and I/O ratios have been shown to be much lower under RC conditions compared to under OA conditions, RC conditions are recommended in polluted environments, such as tunnels and/or heavy traffic to reduce in-vehicle pollution.

2.4 Modelling AERs and I/O pollutant ratios

The time and cost-intensive nature of measuring both AERs and I/O ratios in vehicles means that it is not feasible to perform measurements on every vehicle on the market. As such, mathematical models are an attractive option for estimating in-cabin pollutant levels across the wider vehicle fleet. Models need to be general enough that they can be applied beyond a handful of vehicle models and without requiring a large number of input parameters or decisions by the user. However, they also need to be specific enough to capture inter-vehicle differences in in-cabin pollution. The most relevant models to the study are described below.

2.4.1 Vehicle AER models

An early predictive model of air infiltration into moving and stationary vehicles was presented by **Fletcher and Saunders (1994)** for a limited selection of vehicles. The model was based on vehicle or wind speed and empirically derived leakage coefficients. It was subsequently validated by **Ott *et al.* (2008)**, who observed a good agreement with experimental data obtained using CO as a tracer in a small selection of cars. **Ott *et al.* (2008)** also extended their measurements beyond those from the earlier study to include AER measurements under recirculation settings, with open windows and various vehicle speeds.

Knibbs *et al.* (2009) described a systematic evaluation of AERs in six stationary and moving Australian cars covering an age range of 18 years and four ventilation settings. Sulfur hexafluoride was used as a tracer gas. The authors reported associations between vehicle speed (from 0 to 110 km/h) and AERs that were well represented by standard least-squares linear regression models. **Fruin *et al*. (2011)** described the largest study of in-vehicle AERs to date, involving the use of occupant-generated CO_2 to measure AERs for 59 vehicles that were representative of the Californian fleet. Using a multiple linear regression model they were able to capture 70% of the variability in the AER on the basis of four predictive variables: vehicle age, mileage (which is usually correlated with age), manufacturer, and speed. The variable with the largest effect on AER was determined to be speed (as discussed in Section 2.3). This will influence the choice of vehicle selection and this is discussed later in Section 5.

Hudda *et al.* (2012) compiled the data from **Fruin *et al*. (2011), Ott *et al.* (2008)** and added some additional data to develop a generalised estimating equation (GEE) model that explained 68 to 79% of the variability in AERs for 73 vehicles. This model for predicting AER varies included the following variables: speed, ventilation setting, vehicle type and vehicle manufacturer.

2.4.2 Vehicle I/O models

Knibbs *et al.* (2011) reviewed the literature regarding I/O models for ultrafine particles in passenger vehicles and identified only two at that time – one based on empirical data **(Knibbs *et al.*, 2010)** and one that was based on parameters derived from other models **(Xu and Zhu, 2009)**. Since then, **Hudda *et al.* (2011)** have described an empirical model relating on-road to in-cabin UFP concentrations. These I/O models highlighted the dominant effect of AER on the I/O ratio, with the AER explaining up to 81% of in-vehicle UFP levels **(Knibbs *et al.*, 2010)**. By using data from **Knibbs *et al.* (2010)** and **Hudda *et al.* (2011)** to generate the largest dataset of passenger vehicle I/O ratios, **Hudda *et al*. (2012)** found that up to 79% of the variability in the I/O ratio could be explained from the vehicle speed, ventilation setting, speed, and vehicle age.

Knibbs *et al.* (2010) successfully adapted an indoor model to predict in-vehicle UFP concentrations during trips through the M5 East tunnel in Sydney. Standard mass-balance models for predicting in-cabin concentrations of UFPs using on-road concentrations can be readily adapted to gaseous pollutants. This approach is therefore also suitable for modelling NO_2, and this model is given as:

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

Equation 1

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)

The modelled and measured concentrations from **Knibbs *et al.* (2010)** are shown in **Figure 7-2**.

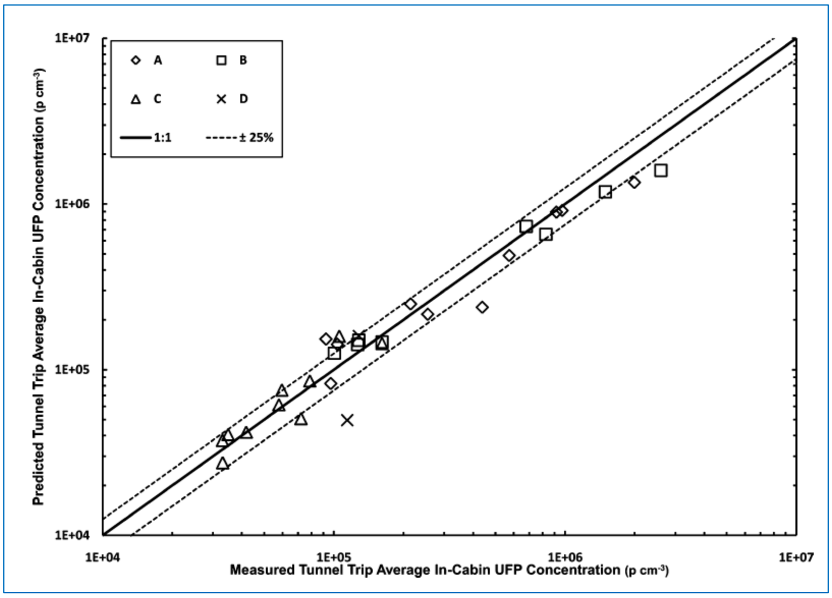


Figure 2-2: Measured and model-predicted in-cabin tunnel trip average UFP concentration (Knibbs *et al.*, 2010). A, B, C and D refer to different ventilation settings.

Many of the parameters in the full form of the model are not required when modelling vehicle cabins and only key parameters are required: on-road concentration, AER, cabin volume and time. Cabin volume can be determined with sophisticated tracer gas methods but manual measurement gives results that are comparable **(Ott *et al.*, 2008)**.

Reactions of NO_2 with indoor surfaces can lead to significant decreases in NO_2 concentrations, particularly when air exchange is low at around one air exchange per hour **(Spicer *et al.*, 1989)**. The loss rate *R* of a pollutant (also termed deposition rate) is dependent upon the deposition velocity of the pollutant and the surface-to-volume ratio of the environment e.g. building or vehicle cabin. The equation for calculating the loss rate *K* is given as **(Dimitrouopoulou *et al.*, 2001)**:

$$K = \frac{v_d A}{V}$$

Equation 2

Where v_d = deposition velocity (in h^{-1})

A/V = Surface-to-volume ratio for the building or vehicle

Literature values of the NO_2 loss rate indoors range from 0.94 – 1.04 h^{-1} **(Yang *et al.*, 2004)**, but the NO_2 loss rate in a vehicle cabin is not well constrained. It has been shown that for low AERs in vehicles, particle concentrations decrease and this is attributed to losses to surfaces **(Fruin *et al.*, 2011)**. It is also possible that under RC conditions, concentrations are reduced by air passing through the in-cabin filters.

The loss rate is difficult to measure in the field as it requires a burst of NO_2 and no interference from other NO_2 sources. However, it can be reliably estimated from the relationship between the vehicle cabin surface-to-volume ratio and reported NO_2 loss rates from the literature **(Dimitrouopoulou *et al*., 2001; Yang *et al*., 2004)**. If the loss rate is known, the loss of NO_2 can be incorporated as a loss term in **Equation 1**. The effect of NO_2 loss may be assessed by comparing model predictions of NO_2 concentrations with and without a loss correction factor.

2.5 Summary and implications for study

From the work described by **Hudda *et al.* (2012)**, which includes by far the largest and most up-to-date AER model, it is apparent that a reasonably large proportion of variability in AER for a given vehicle (up to 79%) can be captured using information that can be obtained without the need for AER measurements. These predicted AERs can then in turn be used to estimate in-vehicle pollutant exposures. For the RMS study it is proposed that the **Hudda *et al.* (2012)** model be validated against measurements on a group of Australian vehicles spanning a range of ages to confirm its local applicability.

Most modelling of vehicle I/O ratios has focused on ultrafine particles. However, generic mass-balance models successfully applied to predict in-vehicle tunnel trip concentrations of ultrafine particles can be applied to NO_2. Loss terms can be added to account for the sink effects of surface reactions. Given an on-road NO_2 concentration the average in-vehicle concentration for a specified trip length can be estimated.

3 MEASUREMENT METHODS

3.1 Air exchange rates

AERs can be estimated from this information using the well-defined empirical relationships between variables such as vehicle speed and ventilation setting **(Charlesworth, 1988)**. However, some of the required parameters can be difficult to determine in practice e.g. cabin volume. This makes direct measurement of AERs an attractive alternative that also has the advantage of removing the reliance on assumptions inherent in estimating AERs.

3.1.1 Measurement approaches

The standard measurement approach for quantifying AERs uses a tracer gas to determine how much air enters a space over time **(Awbi, 2003)**. Tracer gas testing permits direct measurement of air exchanges. Various options are identified in ASTM *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution* **(ASTM, 2006)**. These options include the initial injection of a tracer gas into an air space, followed by a characterisation of the decay in concentration due to dilution with incoming air, a constant injection of tracer gas to measure the dilution of its concentration by incoming air, or a constant-concentration approach where the level of tracer is held constant to determine dilution. All three methods are based on the same fundamental continuity equation which assumes uniform mixing of the tracer **(Charlesworth, 1988)**:

$$V\frac{dC}{dt} = Q(C_{ext} - C_{(t)}) + F$$ **Equation 2**

Where:

V = effective volume of an enclosure (m^3)

Q = air flow rate through an enclosure ($m^3\ s^{-1}$)

C_{ext} = concentration of tracer in external air

$C_{(t)}$ = concentration of tracer in internal air at time t

F = production rate of tracer from all internal sources

t = time

The three methods have advantages and disadvantages. The concentration-decay method is simplest to implement and analyse and doesn't require highly specialised equipment, but is unsuited to high AERs (such as a vehicle cabin when air is being drawn from outside by the ventilation system) where the decay curve cannot be accurately registered **(Kvisgaard, 1995)**. The constant-injection technique can be used over a wide range of AERs, but is more involved to analyse and interpret than the concentration-decay method. The constant-concentration technique is similarly useful in a diverse range of conditions, but requires specialised equipment to control tracer levels **(Charlesworth, 1988)**. In general, the constant-injection and constant-concentration methods yield more accurate and precise estimates of the true AER than the concentration-decay method **(Sherman, 1990)**.

Numerous tracers have been described in the literature **(Sherman, 1990)**. Some of the more commonly encountered examples include:

- Carbon dioxide (CO_2)
- Sulfur hexafluoride (SF_6)
- Nitrous oxide (N_2O)
- Freon
- Helium (He)

A good tracer should gas have a negligible background concentration, be non-toxic, non-combustible, non-reactive and readily measurable by instrumentation. SF_6 has been widely used historically, including in previous Australian studies of vehicle cabin AERs **(Knibbs *et al.*, 2009)**. However, it requires complex and expensive instrumentation. Practical considerations regarding tracer selection are especially important in the dynamic and challenging in-cabin microenvironment. For these reasons, CO_2 is an ideal tracer because of its ease of measurement using portable instrumentation, negligible toxicity at in-vehicle levels, and because passengers are used as the tracer source it doesn't require transport and storage of tracer gas cylinders. It has been shown to be a fast, effective and low-cost method for performing AER measurements for diverse vehicle fleets **(Fruin *et al.*, 2011)**.

3.1.2 Applications to in-vehicle AER

Fruin *et al.* (2011) documented that at a fixed vehicle speed (constant AER), in-vehicle CO_2 concentrations change until an equilibrium concentration is reached whereby the production of CO_2 from vehicle occupants is balanced by the losses of CO_2 due to exchange of low CO_2 concentration outside air (i.e. the background level) with high CO_2 concentration in-cabin air. This difference is typically hundreds or thousands of parts per million (ppm) of CO_2, and is therefore easy to measure with high accuracy. This method is a variation on the constant-injection technique.

Importantly, the CO_2-based work of **Fruin *et al.* (2011)** agreed well with the SF_6-based measurements of **Knibbs *et al.* (2009)**, with an overall R^2 of 0.83. This agreement was strong to the point where the two data sets were statistically indistinguishable **(Hudda *et al.*, 2012)**. This highlights the validity of the simpler to implement, faster and cheaper CO_2 method when compared to the more involved and expensive SF_6 approach.

Knibbs *et al.* (2009) measured ultrafine particles (UFPs) in a Sydney tunnel road (4 km in length) and nearby above-ground roads. The effects of ventilation on UFP concentration AERs was measured by using sulfur hexafluoride (SF_6) as a tracer. Their methods involved using an Innova 1412 (Lumasense Technologies, Ballerup, Denmark) photo-acoustic field gas monitor and Innova 1303 multipoint sampler and doser. SF_6 was constantly administered into the HVAC system inlet between the front windscreen and bonnet and continuously measured. The constant injection technique was used due to its suitability for use in conditions of high ACH where ventilation used external air on the first and third fan settings. For ventilation settings where recirculate was used with fan setting one or where no ventilation was used and air could only enter the vehicle via infiltration, an SF_6 concentration-decay approach was used. Air samples were taken at the passenger side footwall vent, the passenger side right dashboard vent, and the driver's side right dashboard vent. Once tracer concentrations were stabilised (~ 10-15ppm after 15 minutes) dosing stopped and a ventilation setting was chosen on the vehicle. During testing, vehicles were driven to speeds of 0 km/h, 60 km/h and 110 km/h in order to determine the effect of speed on AERs. For the concentration-decay method the natural log of the SF_6 concentration (excluding concentrations during dosing) was plotted against time elapsed and the gradient of the regression line was used to determine ACH. Due to the disruption of GPS speed measurements in the tunnel, average speeds were calculated based on the tunnel length and time taken to drive through the tunnel. To account for different wind directions, measurements were distributed evenly between travel directions and tests were performed during stable weather conditions and light winds to avoid bias. Temperature differences between in-cabin and external air of up to 11°C were measured however temperature was not identified as having an impact on infiltration rates.

Knibbs *et al.* (2010) added to their previous (2009) work in 2010 by performing measurements on vehicles of various ages under different ventilation settings in the M5 East road tunnel in Sydney. This study used a TSI 3007 condensation particle counter with sample points located upstream (outside the vehicle next to the HVAC intake) and downstream (near in-cabin air supply vents) of the HVAC system. Alternating samples of inside and outside vehicle concentrations were obtained by use of a valve controlled by a data logger. The line was flushed after alternating for 10-15 seconds and then a 10 second measurement was obtained.

Hudda *et al.* (2012) measured AERs and I/O ratios for vehicles in New York, and incorporated the work done by Knibbs to develop a model for estimating the in-vehicle passenger exposure to UFPs. In Hudda's New York study CO_2 was used as a tracer gas with measurements made by TSI Q-Trak model 7565 (TSI Inc., MN, USA, model discontinued in 2011) or LI-COR Li-820 (LI-COR Biosciences, NE, USA) which measure CO_2 by non-dispersive infrared (see **Section 3.2**). 308 AERs were measured for recirculate ventilation settings and 145 AERs were measured under outside air intake settings.

3.1.3 Summary

Based on the findings of the 2 largest studies of in-vehicle AER performed to-date, a CO_2-based constant-injection method (from the respiration of vehicle occupants) is well-suited to measuring AER inside vehicles in terms of accuracy, precision, cost and safety.

3.2 Carbon dioxide

Many different types of CO_2 analyser are available, and the characteristics (precision, response time, *etc*.) and cost of the options have been summarised in this Section of the Report. Air quality monitoring equipment suppliers and manufacturers were approached to determine hire costs and indicative lead times for the delivery of each type of instrument.

3.2.1 Cavity ring-down spectroscopy

The Picarro G2201-i (**Figure 3-1**) is a cavity ring-down spectrometer based on a near-IR laser to measure sample gas passed through an optical measurement cavity. According to Picarro the instrument has an effective path length of up to 20 km inside the cavity, which results in high precision, and low-volume cavity to ensure better temperature stability, faster gas exchange, lower noise and higher sensitivity. The stability of the system means that minimal calibration is required **(Picarro, 2015)**.

The G2201 can be used for real-time CO_2 measurements. The Picarro instrument laboratory grade while being robust enough to be used for mobile (on-road and off-road) applications.

Figure 3-1: Picarro G2201-i (source: Picarro, 2015)

3.2.2 Electrochemical cells

The Tango TX1 is a portable, long-life, single-gas monitor that is most commonly used for for personal protection. It is a diffusion instrument for use in detecting and measuring gas present in open space. There are up to four sensor options (CO, H_2S, NO_2 or SO_2) that can be configured.

Tango TX1 measures gas at two second intervals, and continuously logs data every ten seconds. The measurement range is 0 – 1000 ppm with 200 ppb accuracy. The data log can store approximately three months of data for a unit that is on 24 hours a day.

The instrument battery powered and is compact enough to be hand held and thus allows for easy mobility.

3.2.3 Non-dispersive infrared spectroscopy

The LI-COR Li-820 (**Figure 3-2**) uses a non-dispersive infrared (NDIR) detection technique and is pump driven, thus allowing a fast response time (seconds). The Li820 has 1 ppm signal noise at 370 ppm CO_2, and a range of 0-20,000 ppm.

The unit is compact, lightweight design with low power (14 W) requirements, enabling mobility and easy configuration across multiple vehicles.

Characteristics:

- Data reported at up to 1 Hz
- 1 ppm signal noise at 370 ppm CO_2
- Range: 0 – 20,000 ppm
- Lightweight (1 kg)
- Battery power option (14 W)

Figure 3-2: LI-COR Li-820 Continuous CO_2 Analyser

3.2.4 Infrared

The Recordum EC Airpointer uses infrared to measure CO_2 concentrations ranging between 0 and 2000 ppm. The response time for the Airpointer is 25 seconds. The instrument requires relatively low power supply (35 W) and weights 10 kg, making it suitable for mobile applications.

This instrument also features the capability of measuring other gaseous pollutants such as O_3, SO_2, NO, NO_2, CO and VOCs using electrochemical cell technology. In addition the instrument can also be configured to measure TSP, PM_{10}, PM_4, $PM_{2.5}$ and PM_1 using an optical sensor.

3.2.5 Gas sensitive semi-conductor

The Aeroqual AQM65 is a compact air quality monitoring station that allows for continuous measurements of gaseous (CO_2, CO, O_3, SO_2, NO, NO_2 and VOCs) and particulate (PM_{10} and $PM_{2.5}$) concentration.

The CO_2 analyser module incorporates non dispersive infrared receptor (NDIR) technology. NDIR is highly selective to CO_2 and therefore well suited to measuring the gas in ambient air. The range in measurement concentration is 0 to 2000 ppm with a response time of 10 seconds. Air is actively sampled by pump and travels through a glass and Teflon coated inlet system to the CO_2 analyser module.

Characteristics:

- 10 second data resolution
- Accuracy – 3% of ready or 10 ppm
- Range: 0 – 2000 ppm
- Light weight (12 kg)
- Battery power option

Figure 3-3: Aeroqual AQM65 Continuous CO_2 Analyser

3.2.6 MidIR Absorption Spectroscopy

The CT3000 OEM analyser provides continuous and real time monitoring of multiple gases in automotive process testing and analysis. Configured as an extractive system, it provides accurate and sensitive measurements of gas composition, of up to ten gases simultaneously including CO_2.

The CT3000 is fast response featuring measurement frequency of up to 10Hz. The measurement range for CO2 is 0 to 15,000 ppm ± 2%.

For mobile use the instrument would require fit-out that includes rack springs and does not have a battery power option.

3.2.7 Summary

The various instrumentation available for measuring CO2 concentrations as described in Section 3.2 are summarised and evaluated in **Table 3-1**. In previous AER studies, in-vehicle CO_2 has been successfully measured using portable instruments such as the TSI Q-Trak and the LI-COR Li-820. Both units use a non-dispersive infrared (NDIR) detection technique, but the Li- 820 is pump driven, thus allowing a faster response time than the Q-Trak unit (several seconds versus 20 seconds). The Li-820 has 1 ppm signal noise at 370 ppm for CO_2, and a range of 0-20,000 ppm. Given than in-vehicle CO_2 levels reach around 2,000-3,000 ppm, compared with an external concentration of around 400 ppm, this instrument should be sufficient for the study.

Table 3-1: Instrument options for CO_2 measurement

Instrument option			CO2_01	CO2_02	CO2_03	CO2_04	CO2_06	CO2_07
Type			Gas analyser	Gas analyser	Gas analyser	Gas analyser	Gas analyser	Gas analyser
								
Company			**Picarro**	**Tango**	**LI-COR**	**Recordum**	**Aeroqual**	**Cascade Technologies**
System			**G2201-i**	**TX1**	**LI-820**	**EC Airpointer**	**AQM-60**	**CT3000**
Description			**Lab grade analyser**	**Personal protection instrument**	**Continuous CO_2**	**Active electrochemical system**	**Compact air quality monitoring station**	**Extractive gas analyser**
Web			http://www.picarro.com/	http://www.indsci.com/	http://www.licor.com/	http://www.recordum.com/	http://www.aeroqual.com/	http://www.cascade-technologies.com/
Dimensions (mm)			43 x 18 x 45 cm	99 x 51 x 35 mm	23 x 16 x 8 cm	370 x 270 x 540 mm	422 x 422 x 148 mm	243 x 312 x 463 mm
Weight (kg)			26 kg	126 g	1 kg	10 kg	12 kg	30 kg
Operating temperature range (°C)			-10 - 45°C	-20 - 50°C	-25 - 45°C	5 - 40°C	5 - 40°C	5 - 45°C
I/O interface			RS232, Ethernet, USB	LCD Display	RS232, USB adaptor	Ethernet	Ethernet, Wifi	Ethernet, 4-20mA
Supply voltage (V)			100 - 240 VAC	3.6 volts	12 - 30 VDC	115 - 230 VAC	100 - 240 VAC	120 VAC
Suitability of use in a moving vehicle			Has been used for this application in the past with significant consideration of the mounting	Deemed suitable	Deemed suitable	Deemed suitable	Deemed suitable	Would require fit-out (rack, springs)
Power consumption			124 watts (analyser), 35 watts (pump)	Lithium ion battery (3 years continuous)	3.6 watts	35 watts	Unknown	Unknown
Pollutant	CO_2	Technique	Carbon isotope	Electrochemical	Non-dispersive infrared	Infrared	Gas sensitive semiconductor	MidIR Absorption Spectroscopy
		Range	380 - 2000 ppm	0 - 1000 ppm	380 - 20,000 ppm	0 - 2000 ppm	0 - 2000 ppm	0 - 15,000 ppm
		Accuracy	200 ppb + 0.05% of reading	Unknown	<3% of readings	+/- 50 ppm +2% of readings	<3% of reading or 10 ppm	+/- 2 %
		Response	~30 seconds (10 - 90%)	14 seconds (T90)	Unknown	25 seconds	10 seconds (estimate)	Up to 10 / second
		Lower detectable limit	200 ppb (12C), 10 ppb (13C)	1 ppm	3% of readings	6 ppm	10 ppm	10 ppm
Price	Basic	Hire	$5k / month (AGL)	Unknown	N / A	N / A	N / A	$24k / month

Instrument option			CO2_01	CO2_02	CO2_03	CO2_04	CO2_06	CO2_07
Type			Gas analyser	Gas analyser	Gas analyser	Gas analyser	Gas analyser	Gas analyser
								
	unit Cost	Purchase	$100k / unit purchase	Unknown	$6k / unit purchase	$15k / unit (single gas)	$25k / unit (single gas)	N / A
	Other		Calibration gas		$350 (pump)		Battery power source	Calibration gas
					Power source			Battery power source
Availability			Available for lease (AGL)	Unknown	10 days shipping (LI-COR)	4 - 6 weeks (EnviSys)	Available for sale (AirMet)	Available for lease (Ecotech)
Location			Sydney		USA	Austria	Auckland	Sydney
Notes					Higher resolution model available	Can combine other gas sensors to reduce cost	Can combine other gas sensors to reduce cost	

3.3 Nitrogen dioxide

Various instruments are also available for measuring NO_2, ranging from low-cost passive sensors to high-grade laboratory instruments. The main considerations for instrument selection for the study are measurement frequency, resolution and size (portability). For example, when sampling ambient air NO_2 concentrations are usually averaged over much longer periods. A passage through a four km long road tunnel at a speed of 80 km/h, on the other hand, only takes three minutes. Sub-minute averaging periods are therefore required to give an adequate spatial resolution. The instrument resolution needs to be sufficient to enable a clear differentiation between in-vehicle and in-tunnel NO_2 concentrations (which in practice means that concentrations need to be available in the parts-per-billion range).

As with the CO_2 instruments, air quality monitoring equipment suppliers and manufacturers were approached to determine hire costs and indicative lead times for the delivery of each type of instrument.

3.3.1 Passive samplers

Passive NO_2 measurement methods, such as diffusion tubes and Ogawa-style samplers, are generally the cheapest approach and provide values in the parts-per-billion range. Passive samplers were also used in the previous study in the M5 East tunnel for NSW Health **(Cains *et al* 2003)**. Whilst we will consider passive samplers in this evaluation of options, they are unsuitable for this measurement campaign. This is because the minimum timescale for measurements using passive samples is hours, and typically days for a precise measurement. Thus they are not suitable for in-tunnel measurements where a sub-minute measurement frequency is required.

3.3.2 Portable monitors

Many hand-held and portable NO_2 monitors are on the market. These are generally based around electrochemical sensors with quite a slow response time (*e.g.* 30 seconds) and a resolution of the order of 50-100 ppb. However, portable monitors can be prone to interference and we believe that such monitors should not be considered for the measurement campaign.

3.3.3 Chemiluminescence analyser

Chemiluminescence NO_x analysers are typically used in ambient air monitoring applications, and have been used in previous studies of in-vehicle NO_2 concentrations **(Chan & Chung, 2003)**. However, whilst well established for ambient monitoring, this method does have some limitations for mobile monitoring. For instance, the measurement cycle is around 60 seconds (rise/fall time <60 seconds to 95%) to calculate NO_2 concentrations. Furthermore, measurement cycles implement adaptive filtering, which reduces measurement uncertainty in a static location; this a catalytic convertor, and further prolongs the duration of measurement cycles. This technology therefore has a longer response time than would be desirable for mobile monitoring in tunnels. Measurement cycle time on a chemiluminescence analyser can be reduced by filtering noise from the measurement, but this reduces the accuracy of measurements.

We propose to use a chemiluminescence analyser as a reference method to check the validity of measurements recorded by the method that is ultimately selected for our investigations. For instance, this could be achieved by taking a chemiluminescence analyser measurements in a static location. Pacific Environment maintains an inventory of such monitors, and as such would be able to provide this to the project at minimal cost.

3.3.4 Cavity Enhanced Laser Absorption Spectroscopy

Cavity Enhanced Laser Absorption Spectroscopy directly measures NO_2 concentrations and this allows for high-frequency measurements at a rate of 200 milliseconds (ms) (**Figure 3-4**). Furthermore, this analyser is capable of precisely measuring NO_2 at a detection limit of 50 parts per trillion (ppt). This machine features an automatic zero calibration, but requires a span gas calibration bottle. Power requirements are relatively low (100 watts), allowing it to be run off a battery pack.

We consider this technique as being a very good candidate for the current monitoring application. Unfortunately, this equipment is not currently available for lease in Sydney, and it would be necessary to source it from LGR (UK). This would have an impact on the project timeline and there may be cost premiums associated with sourcing such instruments quickly from overseas suppliers.

Characteristics:

- Direct measurements of NO_2
- High precision: 0.05 ppb (1σ, 1 s)
- Data reported at up to 5 Hz
- Range: 0.05 – 1000 ppb

Figure 3-4: LGR direct NO_2 analyser

3.3.5 MidIR Absorption Spectroscopy

An extractive gas analyser (Cascade Technologies, CT3000) can record high-frequency measurements every 200 ms. However, this method has a lower detection limit of only 50 ppb, which may not be sufficient for this application. A local supplier has one available for lease at short notice. While we will evaluate the applicability of this instrument further, we anticipate that the lower detection limit may make this a poor candidate.

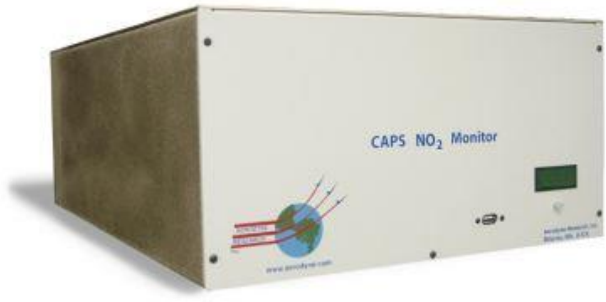
3.3.6 Selected Ion Flow Tube Mass Spectrometry (SIFT-MS)

Selected Ion Flow Tube Mass Spectrometry (SIFT-MS) can also record high-frequency measurements every 200 ms. It can also provide mid-level ppb measurements of NO_2 and is therefore an ideal candidate for this campaign. However, the SIFT-MS is limited by its heavy weight (212 kg), and for ease of applicability across multiple vehicles, the optimal configuration would be to mount the unit and dedicated power supply on a trailer to be towed behind the monitored vehicle. In such a configuration the system would be mounted on springs to minimise vibrations, and batteries would allow for 2-3 hours of data per charge. Potentially a valve can be integrated to allow for simultaneous measurements between in-car and in-tunnel concentrations. The set-up is supplied with calibration bottles, external pump to increase flowrate from vehicle to the instrument, computer control and technical support.

A SIFT-MS (Syft, V200) is available from a Sydney-based instrument provider from early June 2015. The trailer-mounted configuration of this system is seen as a limitation, given the logistical barriers that this poses in terms of vehicle selection (i.e. all vehicles will need to have a tow-bar fitted). However, a key benefit of this technology is its ability to simultaneously measure other pollutants of interest to high resolution and accuracy, which, as noted within the brief, may add additional value to the project outcomes.

3.3.7 Aerodyne Cavity Attenuated Phase Shift (CAPS)

The Aerodyne CAPS NO_2 monitor 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. CAPS offers a linear response at concentrations up to several ppm of NO_2. This range would be adequate for the anticipated in-tunnel NO_2 concentrations. The CAPS requires a source of NO_2-free air for periodic (minutes to hours) baseline measurements. The standard gas flow is 0.85 litres per minute, but lower flow rates with reduced time response can be chosen without loss of sensitivity. The instrument will log 6 GB of data, downloadable via a USB port.



Characteristics:

- Direct measurements of NO_2
- Data reported at up to 1 Hz
- High precision: 1.5 ppb (3σ, 1 sec.)
- Range: 0.01 – 3000 ppb
- Battery power source

Figure 3-5: Aerodyne CAPS direct NO_2 analyser

The CAPS NO_2 analyser weighs 12 kg and can be battery-powered, enabling mobility and relatively easy configuration across multiple vehicles.

3.3.8 Summary

The various instrumentation available for measuring CO_2 and NO_2 concentrations as described in Sections 3.2 and 3.3 are summarised and evaluated in **Table 3-2 and Table 3-3**. As noted above, and within the brief, there is value gathering data on other vehicle pollutants during our investigations e.g., CO, fine particles and PAHs). At this stage, we have identified the SIFT-MS as a candidate technique for evaluating multiple pollutants. During this aspect of the project, we will seek to optimise the ability of our monitoring to include other pollutants of interest. We are also mindful that there may be opportunity to install additional instruments at minimal additional cost to the project, if the majority of costs are associated with the labour/logistics aspect of the work. We will provide RMS with practical options to address these additional pollutants during this work.

Table 3-2: Instrument options for NO_2 measurement (part 1)

Instrument option Type			NO2_01 Gas analyser	NO2_02 Gas analyser	NO2_03 Gas analyser	NO2_04 Gas analyser	NO2_05 Gas analyser
							
Company			**Teledyne**	**Teledyne**	**LGR**	**Aerodyne**	**Cascade Technologies**
Model			**T200**	**T500U**	**NO_2 - 907-0009 (standard)**	**CAPS NO_2 Monitor**	**CT3000**
Description			**Ambient analyser**	**Fast response NO_2**	**Fast response NO_2**	**Fast response NO_2**	**Extractive gas analyser**
Web			http://www.teledyne.com/	http://www.teledyne.com/	http://www.lgrinc.com/	http://www.aerodyne.com/	http://www.cascade-technologies.com/
Dimensions (mm)			178 x 432 x 597 mm	178 x 432 x 597 mm	10" x 38" x 14"	61 x 43 x 23 cm	243 x 312 x 463 mm
Weight (kg)			18 kg (analyser); 7 kg (pump)	15 kg	27 kg	12 kg	30 kg
Operating temperature range (°C)			5 - 40°C	5 - 40°C	5 - 45°C	5 - 45°C	5 - 45°C
I/O interface			Ethernet, RS232, USB	Ethernet, RS232, USB	RS232, Ethernet, USB, analogue	RS232, USB, Ethernet	Ethernet, 4-20mA
Supply voltage (V)			100 -120 V, 220 – 240 V	100 - 250 VAC	115/230 VAC	100 - 250 VAC	120 VAC
Suitability of use in a moving vehicle			Would require consideration of fit-out (rack, springs, etc)	Rack mounting possible but not known how it will respond to vibration	Ruggedised version available, built for use in the field	Rack mounting possible but not known how it will respond to vibration	Rack mounting possible but not known how it will respond to vibration
Power consumption			80 W	80 W	100 W (standard), 150 W (advanced)	10 W	Unknown
Pollutant	**NO2**	**Technique**	Chemiluminence	Cavity Attenuated Phase Shift (CAPS)	Cavity Enhanced Laser Absorption Spectroscopy (LAS)	Cavity Enhanced Laser Absorption Spectroscopy (CAPS)	MidIR Absorption Spectroscopy
		Range	0 - 50 ppb	0 - 1 000 ppb	0.01 - 1000 ppb	0 - 3000 ppb	50 ppb - 1000 ppb
		Accuracy	0.5% of readings above 50 ppb	0.5% of readings above 50 ppb	50 ppt	Unknown	+/- 2%
		Response	<60 s to 95%	<20 s to 95% (non EPA)	1 s	1 second (fast response version)	200 ms

		Instrument option Type	NO2_01 Gas analyser	NO2_02 Gas analyser	NO2_03 Gas analyser	NO2_04 Gas analyser	NO2_05 Gas analyser
							
		Lower detectable limit	0.4 ppb	20 ppt	0.01 ppb	< 1 ppb (fast response version)	50 ppb
Price	**Basic unit cost**	**Purchase**	$13k / unit	$24k / unit	$50k (purchase)	$44k for 2 units	$24k / month (2 gases)
		Hire	$400 / month hire	N / A	N / A	N/A	N / A
	Other		Calibration gas	Calibration gas	Battery power source	Battery power source	Calibration gas
			Battery power source	Battery power source		Calibration gas	Battery power source
Availability			Available for lease (PEL)	4 - 6 weeks (TES)	8 weeks (Ecotech)	Unknown	Available for lease (Ecotech)
Location			Sydney	USA	USA	USA	Sydney
Notes			Long measurement cycle for this application; conversion required	Long measurement cycle for this application	Lead time may be an issue; pump won't run off DC (requires invertor)	No response from manufacturer	Lower detection limit of 20 ppb may not be suitable

Table 3-3: Instrument options for NO_2 measurement (part 2)

Instrument option / Type	NO2_06 Gas analyser	NO2_07 Gas analyser	NO2_08 Gas analyser	NO2_09 Gas analyser	NO2_10 FTIR
					
Company	**Syft**	**Recordum**	**Aeroqual**	**Environment SA**	**MKS**
Model	**V200**	**EC Airpointer**	**AQM-60**	**AS32M**	**MultiGas 2030 HS**
Description	**Trailer mounted lab grade instrument**	**Active electrochemical system**	**Compact air quality monitoring station**	**Fast response NO2**	**High resolution FT-IR**
Web	http://www.syft.com/	http://www.recordum.com/	http://www.aeroqual.com/	http://www.environnement-sa.com/	http://www.mksinst.com/
Dimensions (mm)	900 x 725 x 875 mm	370 x 270 x 540 mm	422 x 422 x 148 mm	Unknown	17.5" x 12.5" x 25.5"
Weight (kg)	212 kg (trailer mounted)	10 kg	12 kg	Unknown	50 kg
Operating temperature range (°C)	10 - 30°C	5 - 40°C	5 - 40°C	0 - 30°C	Unknown
I/O interface	LCD touchscreen	Ethernet	Ethernet, Wifi	Ethernet	Ethernet
Supply voltage (V)	216 - 264 VAC	115 - 230 VAC	100 - 240 VAC	Unknown	120 - 240 VAC
Suitability of use in a moving vehicle	Fitted with springs in trailer configuration but concern from the supplier about durability	Deemed suitable	Deemed suitable	Rack mounting possible but not known how it will respond to vibration	Rack mounting possible but not known how it will respond to vibration
Power consumption	2 - 3 hours battery life per charge	35 W	Unknown	Unknown	Unknown
Pollutant – NO2 – Technique	Selected Ion Flowtube Mass Spectrometer (SIFT-MS)	Electrochemical	Gas sensitive semiconductor (GSS)	Cavity Attenuated Phase Shift (CAPS)	Fourier transform infrared spectroscopy (FTIR)
Pollutant – NO2 – Range	3 - 1000 ppb	5 - 2000 ppb	1 - 200 ppb	0.1 - 1000 ppb	Unknown
Pollutant – NO2 – Accuracy	+/- 10% in ppb range	+/- 5 ppb	<3% of reading or 3 ppb	0.05 ppb at zero, 0.2 ppb at 200 µg/m3	Unknown
Pollutant – NO2 – Response	200 ms	25 s	10 s (estimated)	16 s (rise), 16 s (fall)	5 scans / s
Pollutant – NO2 – Lower detectable limit	50 ppt (VOC), 2 - 3 ppb(NO_2)	5 ppb	1 ppb	0.1 ppb	500 ppb

		Instrument option	NO2_06	NO2_07	NO2_08	NO2_09	NO2_10
		Type	Gas analyser	Gas analyser	Gas analyser	Gas analyser	FTIR
							
Price	**Basic unit cost**	**Purchase**	$200k / unit only	N / A	N / A	$20k / unit with pump	Unknown
		Hire	$22k / month	$15k / unit (single gas)	$25k / unit (single gas)		Unknown
	Other			Battery power source	Battery power source	Battery power source	Battery power source
Availability			Available for lease (TES)	4 - 6 weeks (EnviSys)	Available for sale (AirMet)	Available for sale (Norditech)	Unknown
Location			Sydney	Austria	Auckland	France	USA
Notes			Trailer mount requires tow-bar on each vehicle; possible to measure full suite of VOCs; only one available	Can combine other gas sensors to reduce cost	Can combine other gas sensors to reduce cost		Distributor in Sydney

4 CHARACTERISATION OF SYDNEY TUNNELS

Tunnel characteristics will be taken into consideration in the design of the measurement campaign and the conditions to be included (*e.g*. free flowing traffic or congested traffic) and to account for factors such as the prevailing in-tunnel air quality). To determine tunnel characteristics it is important to first identify the main road tunnels in Sydney that may be incorporated into the monitoring campaign. These are as follows:

- Eastern Distributor
- Lane Cove Tunnel
- M5 East Tunnel
- Sydney Harbour Tunnel
- Cross City Tunnel

Based on information already available to Pacific Environment, as well as any additional information that can be supplied by RMS, each tunnel will be characterised in terms of the following:

- Tunnel geometry (section lengths, gradients).
- Ventilation (air throughput and wind speed).
- Traffic (distributions of volume, composition and speed).
- In-tunnel pollution measurements, including an analysis of data.
- The ability of the tunnel operators to provide real-time data during the measurement campaign.

5 CHARACTERISATION OF SYDNEY CAR FLEET

5.1 Overview

For the purpose of this study there is a need to characterising the car fleet (vehicle type, fuel type, vehicle age, vehicle size and manufacturer) in Sydney for the following purposes:

- To ensure that the vehicles included in the experimental work are broadly representative of the fleet. The selection of test vehicles should reflect the composition (fuel type, vehicle type, vehicle age and vehicle size) of the passenger car fleet in Sydney, bearing in mind that the anticipated opening years for the NorthConnex and WestConnex M4 East projects are 2019 and 2021, respectively.

- To allow a scaling of the in-vehicle NO_2 model predictions (which will be for specific vehicle types) according to the future composition of the fleet.

5.1.1 Fuel type and vehicle type

ABS statistics for a recent (2014) report indicates that the Australian fleet comprises 78.8% petrol powered engines **(ABS, 2014)**. The projected information in the GMR inventory suggests by 2021 the petrol/diesel split by Vehicle Kilometres Travelled (VKT) for passenger cars will remain steady 80:20. We also propose to include a 2015 model year utility vehicle (ute) to examine any potential influence of vehicle type.

The Australian Bureau of Statistics has reported that in 2014 petrol vehicles accounted for just under 80% of the total registered vehicle fleet (all types) **(ABS, 2014)**. Information in NSW EPA's GMR emissions inventory suggests a petrol/diesel split (by VKT) for passenger cars of approximately 80:20 in 2021. Uncertainties remain in the validity of this projection due to results of an examination of vehicle registration (sales) data in NSW recently conducted by the NSW EPA **(Jones, 2015)**. Whilst there are some differences between the geographical coverage and the definitions of vehicle groups, the EPA analysis has highlighted some discrepancies between the actual vehicle sales figures and the inventory projections. NSW EPA note that the actual growth in diesel car sales has been lower than projected in the inventory. For example, the actual NSW-wide diesel proportion of sales in 2014 was 8%, compared with a projection for 2014 in the inventory of 19%.

In the context of the study there will probably be little difference between the AERs and I/O ratios for petrol and diesel cars. However, given the potential increase in the market penetration of diesel, a diesel car will be included in the study to examine any potential effects.

5.1.2 Vehicle age

It has been established in several studies that the age of the vehicle is a significant determinant in the AER and hence in-vehicle concentrations **(Knibbs *et al* 2009; Hudda *et al* 2012)**. An analysis of the petrol and diesel car fleets will be used to inform the selection. For example, **Figure 3-1** shows the projected VKT[3] by vehicle model year in 2021 as a fraction of the total number of vehicles. The most recent vehicle model year available to the study will be 2015. In 2021 it is projected that 2015 model year vehicles will account for around 6% of petrol car VKT and 7% of diesel car VKT.

[3] VKT taken from the Bureau of Transport Statistics Strategic Transport Model.

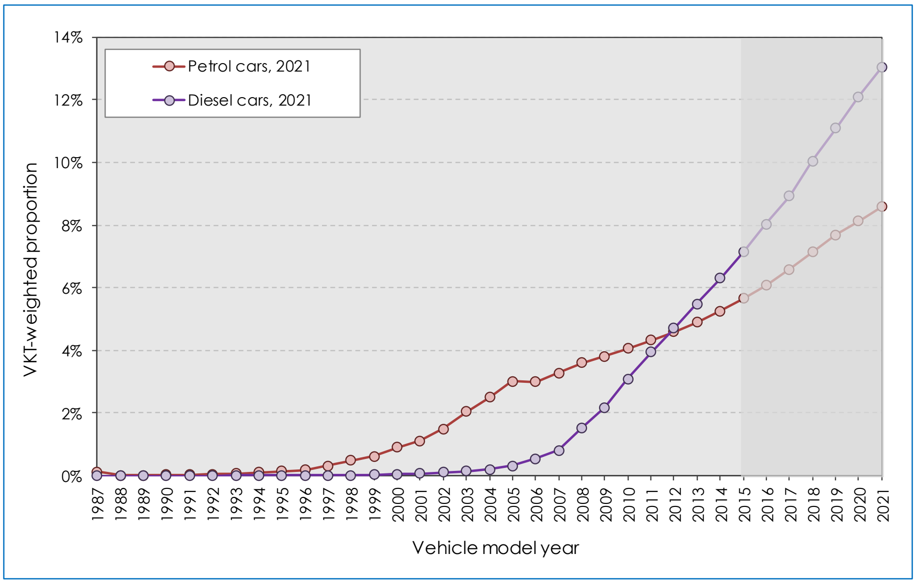


Figure 5-1: Proportion of vehicle activity by model year in 2021 (weighted by VKT)

Figure 3-2 shows the fraction of total VKT in 2021 that is accounted for by different model year ranges. Going from left to right on the x axis, the range of model years included increases by one year for each point. In the case of petrol cars, it is not possible to account for more than around 55% of VKT in 2021 using existing model years (in other words, 45% of VKT will be due to vehicle model years that do not yet exist). The equivalent proportion for diesel cars is 37%. This is when all existing model years going back to 1990 are included. However, the proportions of the oldest vehicles are very small. For example, in the case of diesel cars the model years between 2007 and 2015 will account for 95% of the maximum possible VKT proportion in 2021 using existing models. The corresponding range of model years is 2000-2015. There would therefore be very little point in using pre-2007 diesel vehicles and pre-2000 petrol vehicles. Moreover, to minimise obsolescence of the results, within these ranges there should be a bias in the selection towards newer existing vehicle models. Nevertheless, it would be worth retaining some older models to reflect potential worst-case conditions.

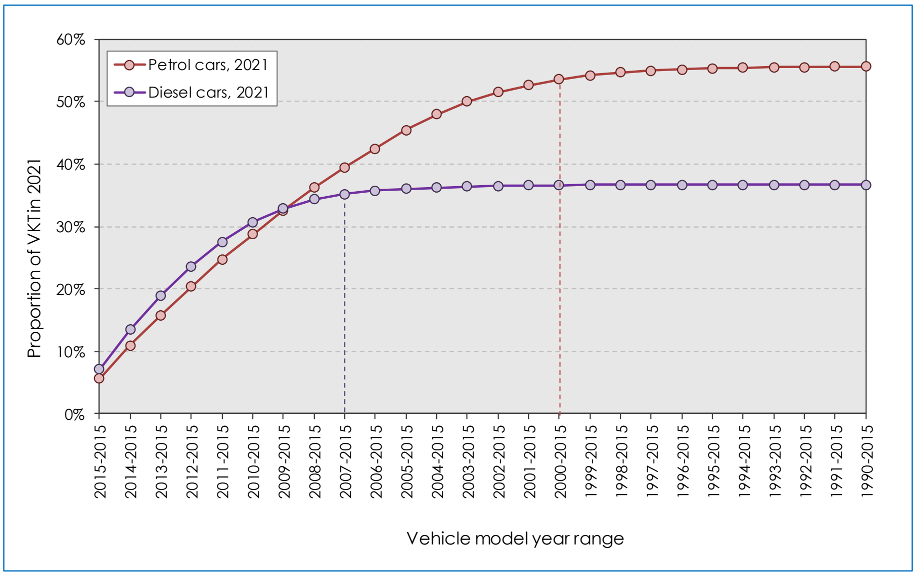


Figure 5-2: Proportion of VKT in 2021 by model year range

5.1.3 Vehicle size

A range of vehicles will be studied in order to have a representative selection of test vehicles, which will likely affect the AER. For the purpose of this literature review a distinction is made between vehicles in nominally 'small', 'medium' and 'large' categories. However, the possibility of using smaller vehicles may be restricted by the need to install measurement equipment.

Vehicle size statistics have also be analysed to determine a representative selection of test vehicles. For the purpose of this literature review, a distinction has been made between vehicles that are in nominally 'small', 'medium' and 'large' categories (see **Table 3-2**). This is based on, for example, engine size.

5.1.4 Vehicle manufacturer

The vehicle manufacturer as well as broader categories such as manufacturer origin (e.g. US or Japan) has a demonstrated effect on the AER **(Fruin *et al.* 2011)**. For example, a 2010 model Honda Civic was shown to have a higher AER than a 2001 model Ford Contour.

The Federal Chamber of Automotive Industries (FCAI) provides information on the new car sales market for Australia. **Table 3-2** provides a summary of the top ten most popular cars sold in 2014. No statistics are available for 2015 at this stage, however, we assume that there would be only minor differences based on the 2013 to 2014 changes **(FACI, 2015)**.

Table 5-1: Top 10 cars sold in 2014 (FCAI, 2015)

Rank	Vehicle	2014	Vehicle size
1	Toyota Corolla	15%	Small
2	Mazda3	14%	Small
3	Toyota Hilux	13%	Ute
4	Hyundai i30	10%	Small
5	Holden Commodore	10%	Medium
6	Ford Ranger	9%	Ute
7	Mitsubishi Triton	8%	Ute
8	Toyota Camry	7%	Medium
9	Mazda CX5	7%	Medium
10	Volkswagen Golf	6%	Small

6 GAP ANALYSIS

In the gap analysis we determine the applicability of the reviewed literature to the assessment of in-tunnel and in-vehicle NO_2 concentrations in Sydney. We then identify key information gaps and limitations that could be addressed through a measurement campaign in Sydney road tunnels.

Studies show that in-vehicle pollutant concentrations are significantly higher whilst driving through tunnels compared to driving on surface roads (discussed in **Section 2.3**). Pollutant concentrations are typically higher at tunnel exits, but detailed high-frequency spatial and temporal measurements throughout a tunnel profile are lacking. For instance, NO_2 was measured in the 2003 study in Sydney's M5 East tunnel for NSW Department of Health **(Cains *et al.*, 2003)**, but at a limited temporal resolution. Real-world information on in-tunnel NO_2 concentrations is therefore required to determine how these vary in time and space.

Another major uncertainty concerns how the concentration of pollutants in tunnels affects the I/O ratios of pollutants in vehicles. The I/O ratio in vehicles is strongly dependent upon the AER, which in turn is dependent on the vehicle type, age and model (as discussed in **Section 2.2**). To determine the applicability of existing AER models to the current vehicle fleet in Sydney, AERs should be measured. This can be achieved by measuring the build-up of CO_2 in vehicles resulting from the occupants' respiration.

Most modelling of vehicle I/O ratios has focused on ultrafine particles, but generic mass-balance models have been successfully applied to predict gaseous pollutants. This could be applied to model in-vehicle tunnel trip concentrations of NO_x pollutants. The importance of in-vehicle deposition of NO_2 is unclear and this can be assess by adding loss terms to models. In the literature, accurate and highly-resolved information regarding in-vehicle NO_2 concentrations are lacking and will be addressed by this study. Constraining the I/O ratio for NO_2 in different vehicle types and at different ventilation settings is required.

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Appendix B METHODOLOGY REPORT

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

Study methodology

NSW ROADS AND MARITIME SERVICES

Job ID. 20336

30 July 2015

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CONTENTS

1 INTRODUCTION

Pacific Environment has been commissioned by NSW Roads and Maritime Services (RMS) to undertake a study entitled *Road tunnels: Reductions in nitrogen dioxide (NO_2) concentrations in-cabin using vehicle ventilation systems*. The study will involve detailed measurements of NO_2 concentrations inside and outside cars that are being driven through road tunnels in Sydney, as well as the development and validation of a simple in-vehicle pollution model. The outcomes of the study will be used to inform the design and operation of future road tunnels in Australia.

1.1 Background to the study

Several major road infrastructure developments are currently planned for Sydney, and tunnels feature prominently amongst these - notably in the NorthConnex and WestConnex 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. The concerns of the community have tended to focus on ambient air quality and the effects of tunnel ventilation stacks. However, given the length of the planned tunnels for NorthConnex and WestConnex, and the likely volumes of traffic in the tunnels, the potential exposure of vehicle occupants to elevated in-tunnel pollutant concentrations is subject to an increasing level of scrutiny.

In many tunnels the demand for fresh air (*i.e.* ventilation sizing) to reduce in-tunnel pollutant concentrations is calculated according to guidelines from the World Road Association (PIARC). The fresh air requirements have traditionally been based upon the in-tunnel concentration of carbon monoxide (CO). In the past, most of the CO was emitted by petrol-engined 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 increased market penetration of diesel vehicles in passenger car fleets (more so in Europe than in Australia to date) has meant that some countries are now considering the use of nitrogen dioxide (NO_2) concentrations for tunnel ventilation sizing. This shift is further supported by evidence (again, mainly from the UK) of an increase in primary NO_2 emissions from road vehicles.

For the planned tunnels in Sydney it is likely that ventilation sizing will be dictated by in-tunnel NO_2 concentrations rather than ambient air quality considerations, and the use of correct assumptions for in-tunnel exposure will therefore be vital. However, there is little evidence in the literature relating to the success or otherwise of in-tunnel NO_2 limits, other than general comments that the management of NO_2 will require the development of reliable monitoring methods and models for in-tunnel concentrations. The 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 the UK Design Manual for Roads and Bridges **(Highways Agency *et al.*, 1999)**, it is not explicitly addressed by PIARC or other Australian guidance.

In response to ongoing concerns about tunnel-related air quality, the NSW Government has established an Advisory Committee on Tunnel Air Quality. The Committee is chaired by the NSW Chief Scientist & Engineer, and includes representatives from several government departments, including RMS. In its *Initial Report on Tunnel Air Quality*[d], the Committee advised that work be undertaken to:

> *'...research, develop and make recommendations on in-tunnel NO_2 limits that would provide an appropriate level of protection in the medium to long term.'*

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

The Committee 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.

This study has been established by RMS to obtain primary data on exposure of vehicle occupants to NO_2. The exposure of occupants to NO_2 in tunnels will be strongly dependent upon the capacity of the vehicle's ventilation system to minimise the AER. The study therefore deals with both AERs and in-vehicle NO_2.

1.2 Objectives

The objectives of the study are as follows:

5. To quantify the AERs and in-vehicle NO_2 concentrations for passenger vehicles (cars only) being driven through road tunnels in Sydney. The vehicles will reflect the types and ages of the current and future passenger vehicle fleet and, as far as possible, will include some 'worst case' examples.

6. To compare NO_2 concentrations inside vehicles with those outside vehicles in the tunnel air, and subsequently determine inside-to-outside (I/O) ratios for NO_2.

7. To understand the influence of vehicle ventilation settings and other parameters on in-vehicle NO_2 concentrations.

8. 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-tunnel NO_2 concentrations and in-vehicle NO_2 concentrations.

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

- In-tunnel pollutant NO_2 concentration profiles (concentration as a function of distance into the tunnel).

- Driving patterns in Sydney for both surface roads and tunnel roads. It will be of interest to see, for example, how speed variation[e] compares for surface roads and tunnel roads.

1.3 Purpose of study methodology report

This Report is the second deliverable from the study, and describes the proposed methodology. The Report contains the following:

- A general overview of the methodology (**Chapter 2**).

- The procedure for the selection of test vehicles (**Chapter 3**).

- The instruments to be used in the vehicles and the treatment of the experimental data (**Chapter 4**).

- The experiments to determine the air exchange rates for the test vehicles (**Chapter 5**).

[e] Emissions from road vehicles are usually stated in models as a function of average trip speed. However, the amount of variation in speed during a trip (for a given average speed) is an important determinant of emissions. Statistical measures such as absolute positive acceleration (APA) or relative positive acceleration (RPA) can be used to describe this variation in speed.

- The experiments to determine the I/O NO_2 ratios for the test vehicles (**Chapter 6**).
- Model validation, development and application (**Chapter 7**).

Comments on the methodology were received from two peer reviewers, and the recommendations from these reviews have been used to improve the methodology. The responses to the specific comments received are presented in **Appendix A**.

2 OVERVIEW OF METHODOLOGY

The study methodology has been designed to address the findings and recommendations of the literature review and gap analysis, and will fill the main gaps in the knowledge within the required time frame. A simplified representation of the overall methodology is shown in **Figure 2-1**, and the various steps are explained in subsequent Chapters.

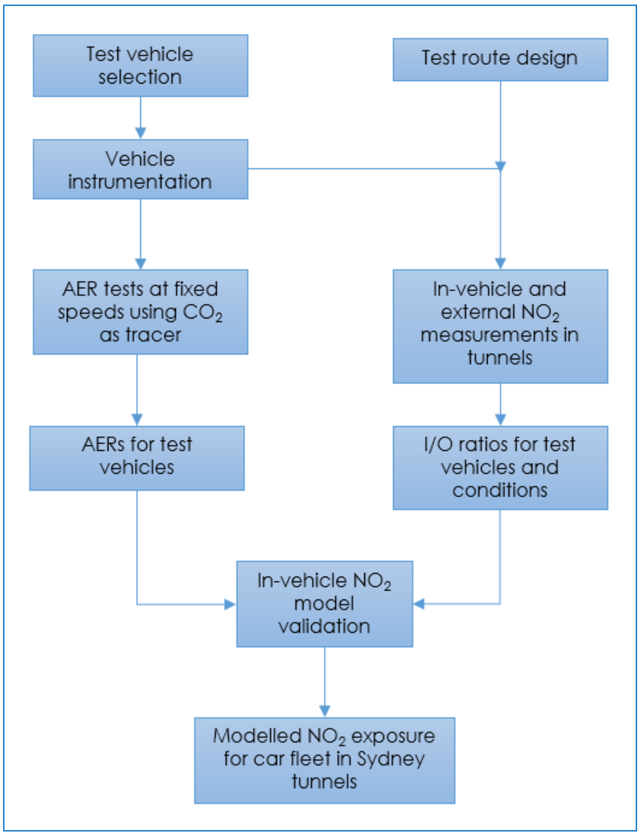

Figure 2-1: Overview of methodology

Several different cars will be used in the experimental work. The cars will be broadly representative of the Sydney fleet and, just as importantly, their characteristics will cover the range of variables in the AER an in-vehicle pollution models. Each vehicle will be instrumented for the measurement of AERs (using a tracer gas), in-vehicle NO_2 and in-tunnel NO_2.

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, and tracer gas testing permits direct measurement of air exchanges. In this study the tracer gas will be CO_2. The AERs for the test vehicles will be determined for steady-state vehicle (and ventilation) operation.

The AER measurements will be used to validate an existing model for AERs and in-vehicle pollutant concentrations. The AER will be one of the key inputs to another model to determine in-vehicle exposure to NO_2 for specific vehicle types. The validated model will then be applied to estimate in-vehicle exposure to NO_2 for the wider Sydney fleet, allowing for the different characteristics of different vehicle types and their representation in the fleet.

3 SELECTION OF TEST VEHICLES

3.1 Overview

The test vehicles will be selected to reflect the range of characteristics of the vehicles in the Sydney fleet, bearing in mind that the anticipated opening years for the NorthConnex and WestConnex M4 East projects are 2019 and 2021, respectively.

The selection of vehicles will be based on the following considerations:

- The likely composition of the car fleet in terms of fuel type, vehicle type, vehicle age and vehicle size in 2021. The VKT by vehicle type will also be considered. This is to ensure that the majority of vehicle models in the test programme will not be 'outliers' in the fleet.

- Car sales by vehicle model.

- Sources of vehicles for the test programme. For example, hire companies tend to have a fleet of relatively new vehicles, and so an alternative source is required for older vehicles (such as staff cars).

- The need to select vehicles that cover a reasonably wide range of AER model parameters, rather than focussing on a narrow range of characteristics. Several older vehicles will therefore be included in the test programme as well as new ones, and vehicles from different manufacturers will be used.

3.2 Selection criteria

3.2.1 Fuel type

The Australian Bureau of Statistics has reported that in 2014 petrol vehicles accounted for just under 80% of the total registered vehicle fleet (all types) **(ABS, 2014)**. The information in NSW EPA's GMR emissions inventory suggests a petrol/diesel split (by VKT) for passenger cars of approximately 80:20 in 2021. However, an examination of vehicle registration (sales) data in NSW has recently been conducted by NSW EPA **(Jones, 2015)**. Whilst there are some differences between the geographical coverage and the definitions of vehicle groups, the EPA analysis has highlighted some discrepancies between the actual vehicle sales figures and the inventory projections. NSW EPA note that the actual growth in diesel car sales has been lower than projected in the inventory. For example, the actual NSW-wide diesel proportion of sales in 2014 was 8%, compared with a projection for 2014 in the inventory of 19%.

In the context of the study there will probably be little difference between the AERs and I/O ratios for petrol and diesel cars. However, due to the relatively high NO_X emissions from diesel cars it is possible that these vehicles may have a more significant 'self-polluting' effect for NO_2 under low-speed conditions. Given the potential increase in the market penetration of diesel vehicles, a diesel car will be included in the study to examine such potential effects.

3.2.2 Vehicle age

It has been established in several studies that vehicle age is a significant determinant of the AER and hence in-vehicle pollutant concentrations **(e.g. Knibbs *et al.*, 2009; Hudda *et al.*, 2012)**. The AER of newer vehicles can be up to an order of magnitude lower than that of older vehicles **(Knibbs *et al.*, 2009)**. It is possible that the AER will increase over time due to seals degrading, and therefore older vehicles will be more susceptible to air pollution in tunnels.

The only way to assess this effect explicitly is to re-measure AERs for vehicles of a certain model and age that were measured in previous studies. However, given that the studies which previously measured AERs were carried out in 2009 and 2011 respectively **(Knibbs *et al.*, 2009; Hudda *et al.*, 2012)**, and the time constraints of this study, it will not be feasible to obtain the corresponding vehicles of the same model and year. Instead, vehicles from the current fleet will be allocated to nominal 'new', 'intermediate' and 'old' age bands.

An analysis of the projected car fleet in the GMR has been used to inform the definition of the age bands and the selection of test vehicles.

Figure 3-1 shows the projected VKT[f] by vehicle model year in 2021 as a fraction of the total (**NB:** the data for petrol and diesel vehicles here are specific to each vehicle type, and are not additive). The newest vehicle model year available to the study will be 2015.

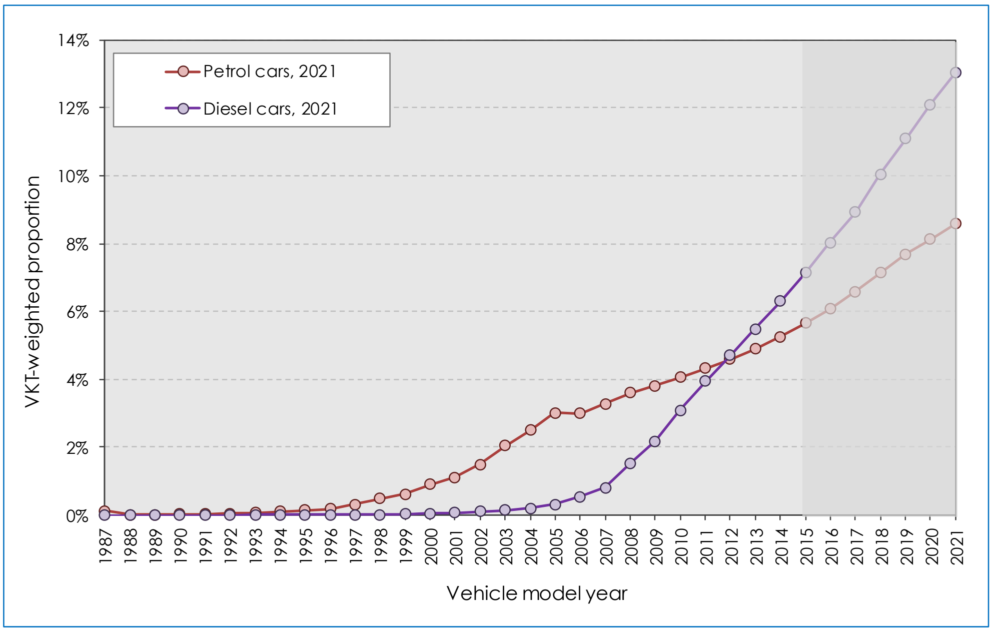

Figure 3-1: Proportion of vehicle activity by model year in 2021 (weighted by VKT)

Figure 3-2 shows the fraction of total VKT in 2021 that is accounted for by different model year ranges. Going from left to right on the x axis, the range of model years included increases by one year for each point. In the case of petrol cars, it is not possible to account for more than around 55% of VKT in 2021 using existing model years (in other words, 45% of VKT will be due to vehicle model years that do not yet exist). The equivalent proportion for diesel cars is 37%. This is when all existing model years going back to 1990 are included. However, the proportions of the oldest vehicles are very small. For example, in the case of diesel cars the model years between 2007 and 2015 will account for 95% of the maximum possible VKT proportion in 2021 using existing models.

In the RMS study the following age bands will be used:

- 2011-2015 model year vehicles will be considered 'new'
- 2006-2010 model year vehicles will be considered 'intermediate'
- Pre-2006 model year vehicles will be considered 'old'.

[f] VKT taken from the Bureau of Transport Statistics Strategic Transport Model.

Although pre-2006 vehicles are not expected to constitute a significant proportion of the vehicle fleet in 2021, the AERs and I/O ratios of older vehicles will be used to establish potential worst-case conditions. Whilst the study will focus on providing actual measurements in Sydney tunnels, the AERs determined for older vehicles in previous studies will be used predict I/O ratios for NO_2 using the model developed by **Hudda *et al.* (2012)**.

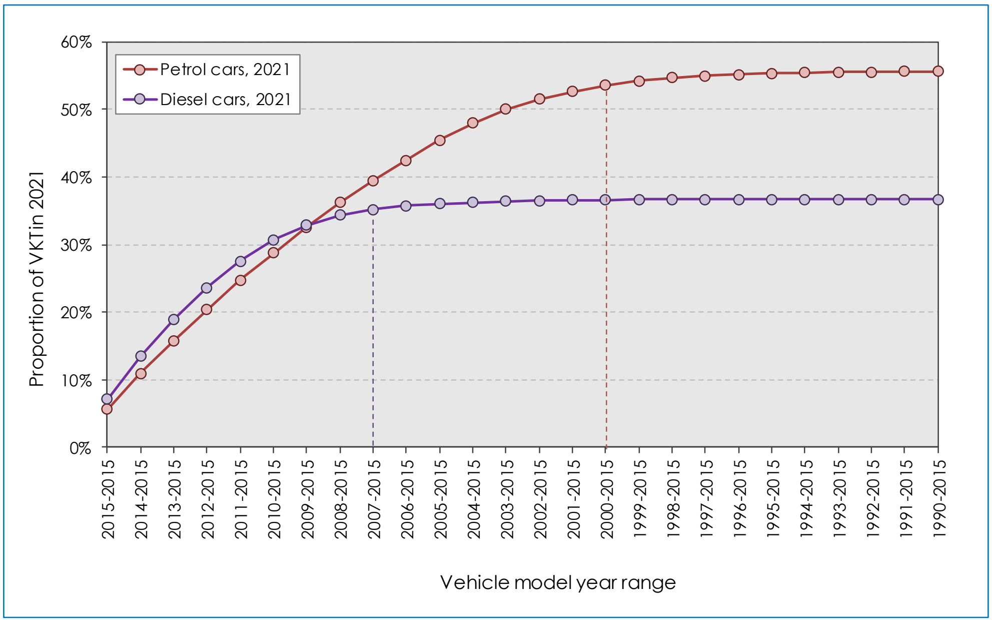

Figure 3-2: Proportion of VKT in 2021 by model year range

3.2.3 Vehicle size

Hudda *et al.* (2012) showed that cabin volume is negatively correlated with AER. **Table 3-1** lists information of vehicle size class, including estimated cabin volume based on US standards **(US Department of Energy, 2015)**. The mid-point of the cabin volume range was used for the AER model estimates shown in **Figure 3-3** and discussed in **Section 3.3**.

Table 3-1: Vehicle Size Class

Size Class (abbrev)	Size Class Detailed: Australia / EuroNCAP / US EPA	Examples	Volume Range (Mid-Point)
S	Small-Medium / Small Family / Compact	Hyundai Elantra, Honda Civic, Mazda3, Toyota Corolla, Volkswagen Golf	2,832 – 3,087 litres (2960 litres)
M	Medium / Large Family / Mid-Size	Chevrolet Malibu, Chrysler 200, Ford Fusion, Subaru Legacy, Volkswagen Passat	3115 – 3400 litres (3260 litres)
L	Large / Executive / Full Size (or US Standard Small-Mid size Station wagon / SUV)	Chevrolet Impala, Ford Taurus, Hyundai Grandeur, Holden Commodore, Toyota Avalon	3400 – 4530 litres

3.2.4 Vehicle manufacturer

The vehicle manufacturer (or country of origin) has a demonstrated effect on the AER. For example, the model developed by **Hudda *et al.* (2012)** has separate 'manufacturer adjustments' for country of origin. Other things being equal, a vehicle manufactured in the US is expected to have an AER that is nearly 50% higher than a Japanese vehicle and about twice as high as a vehicle manufactured in Germany. Australian vehicles are estimated to be most similar to US vehicles **(Knibbs, 2015)**. To account for this we have included a spread of manufacturers from Germany (best), Japan/South Korea (intermediate), and the US/Australia (worst).

The Federal Chamber of Automotive Industries (FCAI) provides information on the new car sales market for the whole of Australia. **Table 3-2** provides a summary of the top ten most popular cars sold in 2014. If possible, we will also aim to include popular vehicles.

Table 3-2: Top 10 cars sold in 2014 (FCAI, 2015)

Rank	Vehicle	2014	Nominal vehicle size
1	Toyota Corolla	15%	Small
2	Mazda 3	14%	Small
3	Toyota Hilux	13%	Ute
4	Hyundai i30	10%	Small
5	Holden Commodore	10%	Medium
6	Ford Ranger	9%	Ute
7	Mitsubishi Triton	8%	Ute
8	Toyota Camry	7%	Medium
9	Mazda CX5	7%	Medium
10	Volkswagen Golf	6%	Small

3.3 Vehicle matrix

Note on vehicle sample size

The vehicle sample size will essentially be constrained by the timeframe for the study, which will permit a measurement campaign of no more than around two or three weeks, and the availability of measurement equipment, which will allow only one vehicle at a time to be tested. A sample size calculation to ensure statistically significant results which takes into account the size of the vehicle population (*e.g.* up to 100,000 vehicles per day) and the variance in the measured parameters would tend to suggest a large number of test vehicles. Given that the primary purpose of the measurements is to test an existing predictive model that is based on a large number of vehicles, the use of a relatively small sample size is not considered to be problematic.

A total of nine test vehicles will be included in the study. A target vehicle matrix based on region of manufacture, vehicle age and size is summarised in **Table 3-3.**

Table 3-3 Target vehicle matrix based on vehicle age, region of manufacture and size

Manufacture Region	Model year 'New' (2011-2015)	'Intermediate' (2006-2010)	'Old' (Pre-2006)	Total
European	L	S	M	**3**
Japanese / Korean	S	M	L	**3**
US / Australian	M	L	S	**3**
	3	**3**	**3**	**9**

Cabin volume / vehicle size of small (S), medium (M) and large (L) vehicles has been included as a second-level dimension in the vehicle matrix. A mix of each cabin volume class has been made within each manufacture class (row) and each age class (column). In addition, the volume classes with the lowest AER (high volume) and highest AER (low volume) have been paired with the lowest AER age/manufacturer combination (top left) and highest AER age/manufacturer combination (bottom right), respectively. This extends the range of AER values of the study to the maximum possible.

The sources of test vehicles will be a combination of those from Pacific Environment staff, car sharing websites, and rental car companies. The vehicles available at the time of writing are listed in **Table 3-4** though many more could be added. The expected AERs of these vehicles have also been calculated using the model from **Hudda *et al.*, 2012**, which can predict the AER from the vehicle age, cabin volume and manufacturing region. Cabin volume has been estimated from the vehicle size class as explained in **Section 3.2.3**. The vehicles from this list to be used in the final matrix below have also been noted in the Table.

Based on the target matrix (**Table 3-3**) and the vehicles available (**Table 3-4**), we suggest the final vehicle matrix shown in **Table 3-5**. For each age range, the vehicles have been classified into 'best', 'intermediate' and 'worst' in terms of manufacture region. Additional classifications have been made on vehicle size class. These selected vehicles should therefore yield a range of AERs for the monitoring campaign, as shown in **Figure 3-3**.

It should be noted that it is possible that not all the specific vehicles listed in **Table 3-5** will be available for testing. If this occurs then all efforts will be made to replace them with vehicles of similar age, size and manufacture region such that the target matrix conditions are still satisfied.

It is possible that diesel cars may have increased levels of in-vehicle NO_2 due to the self-polluting effect mentioned in **Section 3.2.1**, and we will endeavour to include a diesel vehicle to test this hypothesis. We do not have a diesel car available from staff, but this may be obtainable from share or rental services. Were one to be used it would most likely be a replacement for a European vehicle since many European models have diesel alternatives.

Table 3-4: Vehicles available to this study and predicted AERs 60, 80 and 100 km/h

In Matrix	Make/model/class	Model year	Age Class	Size Class	Manufact. Region	Predicted AER 60 km/h	Predicted AER 80 km/h	Predicted AER 100 km/h
Pacific Environment Staff								
N	Hyundai Veloster (hatchback)	2012	New	S	JP/KO	4.5	7.2	5.7
Y	Subaru Outback	2006	Old	L	JP/KO	4.6	7.3	5.8
N	Mazda 3 (hatchback)	2011	New	S	JP/KO	4.7	7.5	5.9
N	Hyundai i30 (hatchback)	2011	New	S	JP/KO	4.7	7.5	5.9
N	Honda Civic	1990	Old	S	JP/KO	47.6	76.3	60.3
N	Ford Focus (hatchback)	2009	Int	S	JP/KO	7.6	12.1	9.6
N	Ford Territory (7 seater)	2005	Old	L	US/AU	7.3	11.7	9.3
Y	Hyundai i30	2014	New	S	JP/KO	4.2	6.8	5.4
N	Suzuki Swift	2007	Int	S	JP/KO	5.8	9.3	7.3
N	Mazda 121	2000	Old	S	JP/KO	10.9	17.6	13.9
Share Websites								
Y	Volkswagen Tiguan	2014	New	L	EU	2.3	3.6	2.9
Y	Fiat Punto	2007	Int	S	EU	4.2	6.7	5.3
N	Volkswagen Beetle	2007	Int	S	EU	4.2	6.7	5.3
N	Volkswagen Passat	2002	Old	M	EU	5.9	9.4	7.4
Y	Mercedes Benz	2002	Old	M	EU	5.9	9.4	7.4
Y	Toyota Corolla	2008	Int	M	JP/KO	5.0	8.0	6.3
Y	Holden Astra Wagon	2008	Int	L	US/AU	5.9	9.5	7.5
Y	Ford Fiesta	2004	Old	S	US/AU	10.8	17.3	13.7
Rental								
N	Holden Cruze	2013	New	M	US/AU	5.9	9.4	7.4
Y	Ford Falcon XR6	2013	New	M	US/AU	5.9	9.4	7.4

Table 3-5: Final test vehicle matrix

Expected AER Performance (by Manufacturer Region)	Vehicle make and model by age band: New (2011-2015 model years)	Intermediate (2006-2010 model years)	Old (pre-2006 model years)
Best (EU)	VW Tiguan (2014)	Fiat Punto (2007)	*Mercedes Benz (2002)*
Intermediate (JP/KO)	Hyundai i30 (2014)	*Toyota Corolla (2008)*	Subaru Outback (2006)
Worst (US/AU)	*Ford Falcon XR6 (≥2011)*	Holden Astra Wagon (2008)	Ford Fiesta (2002)
Size Class: Small, *Medium*, Large			

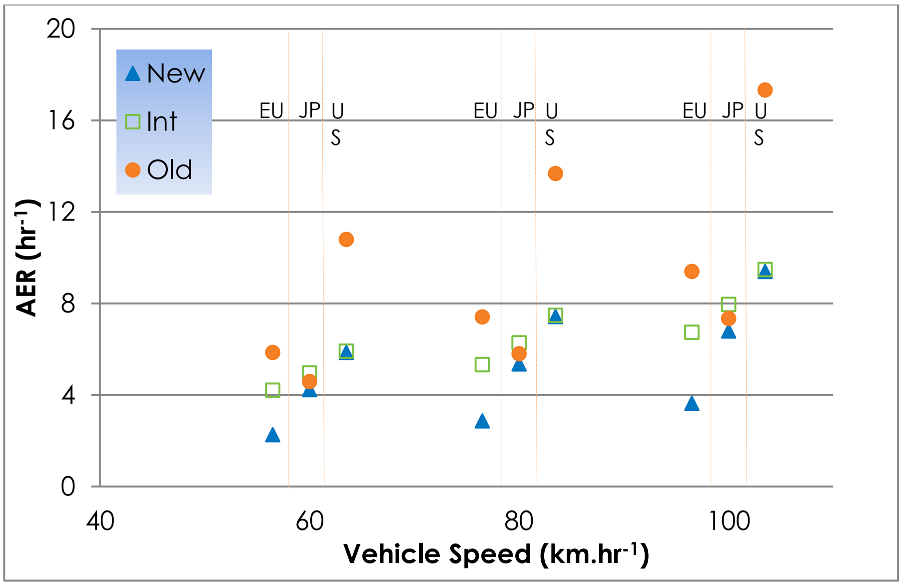

Figure 3-3 Range of AERs for selected test vehicles based on values from Table 3-4. Points are coloured according to vehicle age (New, Intermediate or Old) and horizontally aligned (at each speed category) according to region of manufacture (European, Japanese/Korean, US/Australian)

4 VEHICLE INSTRUMENTATION AND TREATMENT OF DATA

4.1 Vehicle set-up

Each test vehicle will be equipped with the following instrumentation:

- Equipment to determine AERs. This will include:
  - Analysers to measure the in-vehicle and external CO_2 concentration. The vehicle occupants will be the interior source of CO_2.
  - Associated pumps, manifolds and sample lines.
- Equipment to determine NO_2 concentrations. This will include:
  - Analysers to measure the in-vehicle and external NO_2 concentration.
  - Associated pumps and sample lines.
- Equipment to monitor record vehicle operation and position. This will include:
  - An OBD scanning tool and software.
  - GPS
- A video camera to record the characteristics of the vehicle in front of the test vehicle.
- Data loggers and computers.

Given the rapid transit time in tunnels, separate fast-response analysers will be used for in-vehicle and external sampling. It is anticipated that multi-point sampling will be used for each instrument, whereby the sample line has several inlets.

All instruments will be powered from on-board batteries, and all equipment (instruments and batteries) will be installed in the boot of each test vehicle. The maximum sampling duration permitted by the batteries will be determined prior to the field work. Back-up batteries will be carried on-board to avoid loss of data. All instruments will be synchronised to within one second prior to the sampling for each vehicle.

Precautions will be taken to minimise the influence of other potential errors and artefacts. For example, in-vehicle samples will be collected close to the breathing zone of vehicle occupants for representativeness. All inlets/outlets for sample lines will be well sealed. Foam padding will be used to protect the equipment and dampen on-board vibration. Following each measurement, the vehicle cabin will be flushed with outdoor air for 5–10 min to remove any residual pollutants (and CO_2 during AER measurements) prior to the next measurement.

4.2 Carbon dioxide measurement

The specification, cost and practicality of various different instruments for measuring in-vehicle CO_2 concentrations were assessed in the literature review **(Boulter *et al.*, 2015)**. Previous AER studies have shown that expensive, laboratory-grade instruments are not required for the measurement of in-vehicle CO_2. For example, in-vehicle CO_2 has been successfully measured using portable instruments such as the TSI Q-Trak and the LI-COR Li-820. Both these instruments use a non-dispersive infrared (NDIR) detection technique, but the Li- 820 is pump driven, thus allowing a faster response time than the Q-Trak unit (several seconds versus 20 seconds). The Li-820 has 1 ppm signal noise at 370 ppm CO_2, and a range of 0-20,000 ppm. Given than in-vehicle CO_2 levels reach around 2,000-3,000 ppm, compared with an external concentration of around 400 ppm, this instrument will be sufficient for the study. The unit is compact, lightweight design with low power (14 W) requirements enabling mobility and easy configuration across multiple vehicles.

4.3 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 **(Boulter *et al.*, 2015)**.

The main considerations for instrument selection for this study are measurement frequency, resolution and size/portability. For example, a passage through a four kilometre long road tunnel at a speed of 80 km/h takes three minutes. Sub-minute averaging periods are therefore required to give an adequate spatial and temporal resolution. However, when sampling ambient air the NO_2 concentrations are usually averaged over longer periods. The instrument resolution also needs to be sufficient to enable a clear differentiation between in-vehicle and in-tunnel NO_2 concentrations, which in practice means that concentrations need to be available in the parts-per-billion range.

Based on the outcome of the literature review we propose to use two Aerodyne Cavity Attenuated Phase Shift (CAPS) NO_2 analysers, one to measure interior concentrations and the other to measure external concentrations.

The CAPS 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 CAPS instrument can provide response times of up to 1Hz with a NO_2 resolution of approximately 1 ppb and a linear response at concentrations up to several ppm. This range would be adequate for the anticipated in-tunnel NO_2 concentrations. The CAPS requires a source of NO_2-free air for periodic (minutes to hours) baseline measurements. The standard gas flow is 0.85 litres per minute, but higher flow rates with reduced time response can be chosen without loss of sensitivity. The instrument will log 6 GB of data, downloadable via a USB port. The CAPS NO_2 weighs 12 kg and can be battery powered (power requirements are 100 W) enabling mobility and relatively easy configuration across multiple vehicles.

The proposed experimental method would include multipoint sampling for both the in-vehicle and outside-vehicle NO_2. For the outside-vehicle measurements the sampling inlets will be placed at a practical location towards the front of the vehicle that is representative of the ventilation intakes. An identical system will be used to measure the concentration in the cabin. Instrument exhaust will be transported to, and released from, the rear of the vehicle.

Instruments will be zero and span validated/calibrated on a daily basis, and multipoint calibration will be undertaken on a weekly basis.

4.4 Vehicle operation

The operation and position of each test vehicle will be logged continuously so that any parameters that might potentially affect the AER and in-vehicle pollution levels are recorded.

The output from the on-board diagnostics (OBD) port of each vehicle will be recorded using a scanning tool and software. There will be a need to ensure that the selected test vehicles are capable of communicating according to one of the approved protocols (*e.g.* ISO 9141, J1850, KWP2000 or CAN). On-line data acquisition will be achieved via a simple interface that is connected to the serial port of a standard PC having OBD-scanning software. A variety of vehicle operation parameters will be recorded in real time (around 2 Hz). The most important parameter will be vehicle speed, although other potentially useful information will be collected as a matter of course, such as engine speed and engine load. An example output is shown in **Figure 4-1**.

A GPS receiver (*e.g.* Garmin 62S, or equivalent) will also be used to log the location, speed, bearing, trip distance, and altitude of each vehicle. The OBD data and a manual record of vehicle location will be used as back-up where the GPS signal is lost (*e.g.* inside tunnels). A logging frequency of 1Hz will be used.

The following parameters will be recorded:

- Date (GPS).
- Time (GPS).
- Vehicle speed (GPS/OBD).
- Engine speed (OBD).
- Vehicle position (GPS/OBD).

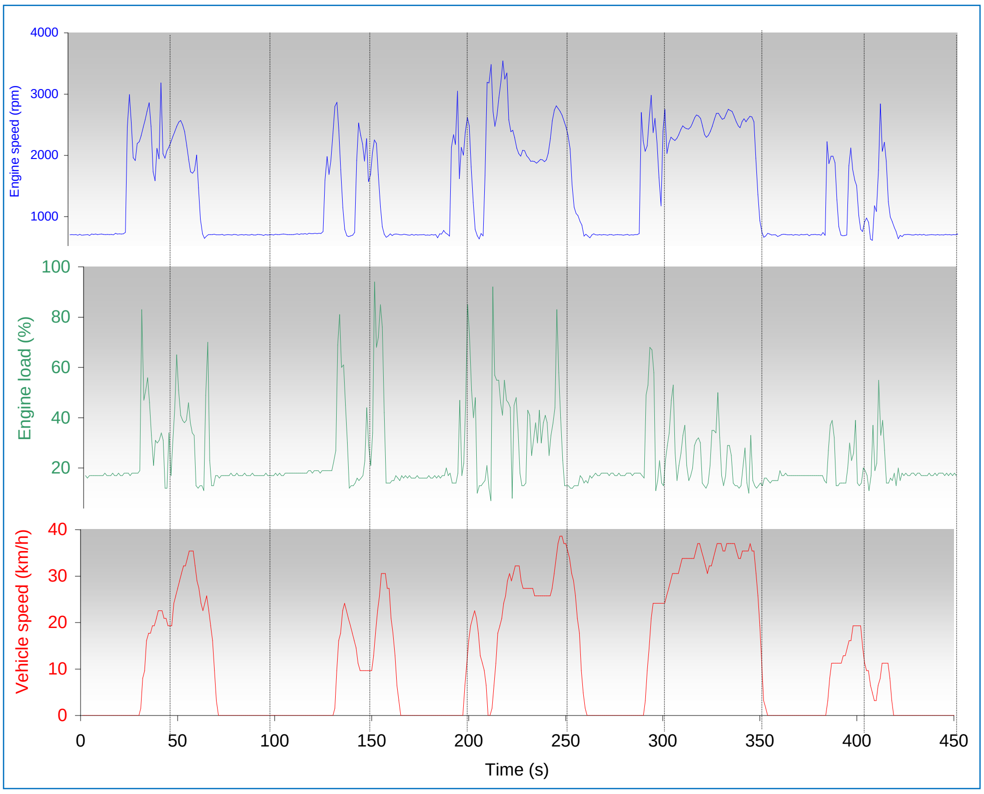

Figure 4-1: Example of OBD output

4.5 Video recording

Each vehicle will be equipped with a forward-facing video camera to continuously record the characteristics of the vehicle in front of the test car. The video information could be useful to explain any unusually high peaks in NO_2. Additionally, this information might be used to correct potential bias if measurements were to occur during periods when, for example, trucks comprise a high proportion of the traffic. It is worth adding that the vehicle in front of the test vehicle should have a proportionally lower impact on the measurements with increased distance into a tunnel.

4.6 Storage, processing and analysis of data

All measurements will be stored on data loggers or laptop computers, and will transferred to the Pacific Environment server and the end of each day. The measurements will then be subjected to established QA/QC precedures to remove or correct artefacts, calibration periods, *etc*.

The effects of the various sampling parameters on the I/O concentration ratio could be determined using statistical techniques such as multi-factor analysis of variance (ANOVA), with exclusion of covariates where there are no significant relationships. However, the primary purpose of the measurements would be model validation, and therefore most of the statistical analysis would focus on descriptive and simple analytical statistics. This applies to both AER and NO_2 measurements.

The NO_2 measurements will be obtained for short averaging periods (probably of the order of 10 seconds). So, in the case of tunnels, for example, we will provide:

- Interior and exterior NO_2 concentrations (and I/O ratios) by time and distance, including an examination of time lags (where observed) between external and in-vehicle concentrations.
- Mean inside-vehicle NO_2 concentration by road section.
- Mean outside-vehicle NO_2 concentration by road section.
- Mean I/O NO_2 ratio by road section.
- I/O NO_2 ratio vs outside-vehicle concentration.

The NO_2 concentration data will be presented graphically and summarised in tables.

4.7 Initial testing

A one-day period will set aside for the initial testing of the instrumentation in order to identify any potential issues with sampling and logistics.

5 MEASUREMENT OF AIR EXCHANGE RATES

The AERs for the test vehicles will be measured directly. 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.

Practical considerations regarding tracer selection are especially important in the dynamic and challenging in-cabin microenvironment. We have adopted the use of CO_2 as the tracer gas. CO_2 is an ideal tracer because of its ease of measurement using portable instrumentation, negligible toxicity at in-vehicle levels, and because passengers can be used as the tracer source it doesn't require transport and storage of tracer gas cylinders. It has been shown to be a fast, effective and low-cost method for performing AER measurements for diverse vehicle fleets.

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)**[g]. 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. These options were considered in the literature review, and it was concluded that the most appropriate approach would be to use the constant-injection method[h]. In fact, occupant-generated CO_2 will be used. This 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 is nearly constant and the CO_2 concentrations inside the car will eventually reach an equilibrium value. The AER for each vehicle and ventilation setting will be calculated using the fundamental continuity equation (**Charlesworth, 1988**):

$$V\frac{dC}{dt} = Q(C_{ext} - C_{(t)}) + F$$ **Equation 2**

Where:

V = effective volume of an enclosure (m^3)

Q = air flow rate through an enclosure ($m^3\ s^{-1}$)

C_{ext} = concentration of tracer in external air

$C_{(t)}$ = concentration of tracer in internal air at time t

F = production rate of tracer from all internal sources

t = time

The AER tests will be conducted under real-world traffic conditions, with each test vehicle being driven at different constant speeds. As the purpose of the AER test is to determine the validity of an existing model for cars in the Sydney fleet, it will be unnecessary to test large number of speeds. We propose nominal speeds of 60 km/h and 100 km/h.

It is noted that that the speed limit in Sydney tunnels is 80 km/h. The aim of using speeds of 60 km/h and 100 km/h is to obtain data for speeds that are both achievable on public roads (low speeds are difficult) and have some separation. Based on previous tests on Australian cars we observed a linear

[g] Active Standard ASTM E741: *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.* http://www.astm.org/Standards/E741.htm

[h] The constant-injection technique can be used over a wide range of AERs and was adopted for the two largest studies of in-vehicle AER performed to-date

increase in AER with speed. So, by covering as wide a range of speeds as possible we will avoid out-of-sample estimation of AER at higher speeds (which makes the data applicable to more driving scenarios; e.g. whether tunnel or otherwise, now or in the future). We would therefore prefer to include 100 km/h to address the wider applicability of the model across road types, and interpolate for 80 km/h. In the previous work we also found that 3 speeds (including stationary) was sufficient, and offered the best compromise between practicality and accuracy.

Suitable roadways and periods will be identified to enable the test vehicles to be driven in a safe and uninterrupted manner at the target speeds and for a sufficient duration (around 20 minutes). Low-traffic conditions will be selected to enable steady-state conditions to be attained and to minimise changes in the outside CO_2 due to the presence of exhaust plumes from other vehicles.

AERs will be determined with windows closed, ventilation set to air recirculation, and the fan set to either 50% or as close as possible to a mid-way setting. For a subset of tests, AERs will also be determined for stationary vehicles and other fan settings.

Where the test vehicles have similar AERs, consideration will be given to adapting the NO_2 measurement part of the campaign to reduce the number of vehicles, and to therefore have more transits per vehicle.

6 MEASUREMENT OF NO_2 CONCENTRATIONS

6.1 Route design and driving

The proposed driving route is shown in **Figure 6-1**. The route has been designed so that it includes the following road tunnels:

- Lane Cove Tunnel
- Sydney Harbour Tunnel
- Eastern Distributor
- M5 East Tunnel.

The route will also include a number of surface roads.

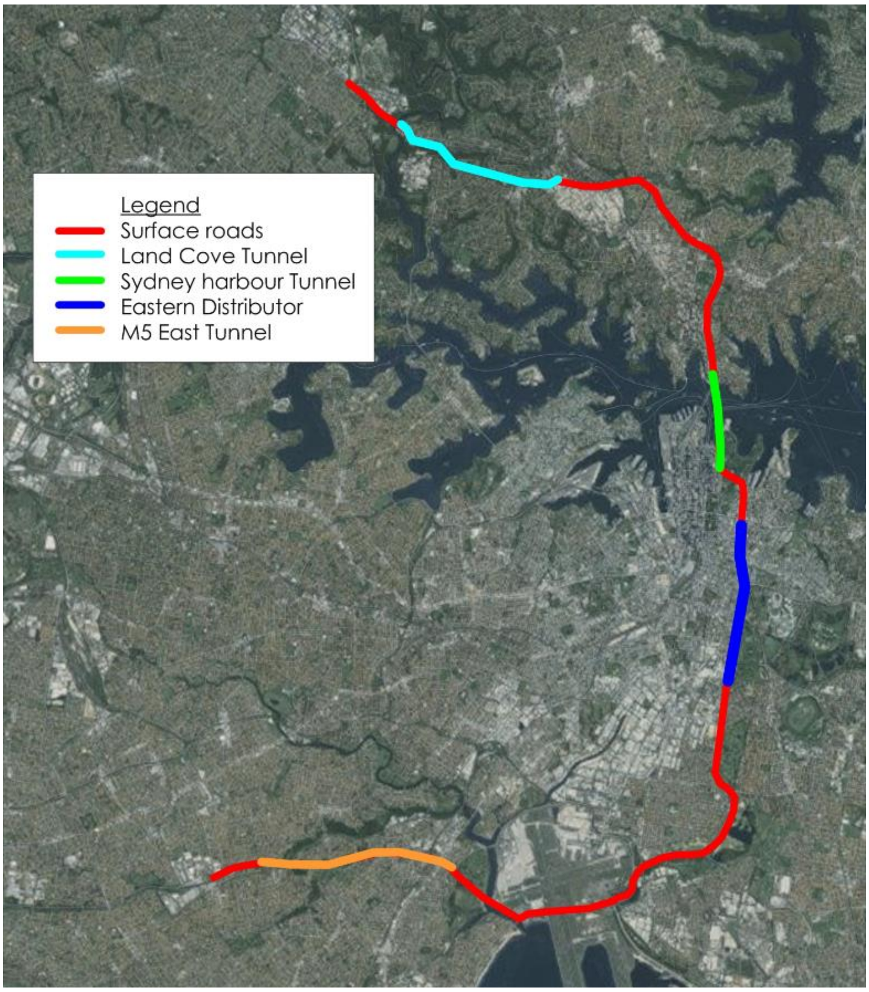

Figure 6-1: Proposed route

The route will maximise the number of runs through each tunnel, as it follows a relatively simple trajectory. The length of this route is 30 km (one way), and a typical travel time would be between 45 and 60 minutes. We have excluded the Cross-City Tunnel from the route as it will result in a significant detour and reduce the rate at which tunnel measurements can be obtained.

Pacific Environment staff will drive the test vehicles along the prescribed route. Prior to the surveys each driver will be instructed to drive as normally as possible, and in such a way that the speed of the test vehicle reflects that of the surrounding traffic. The measurements will be made at various times of day, covering both the peak and off-peak periods.

A passenger will also be present in the test vehicle to operate the logging equipment and to complete an information sheet for each trip. The information sheet will include details such as direction of travel, tunnel entry and exit times, vehicle ventilation conditions and comments on text conditions (adverse weather, congestion, *etc.*).

Measurements will also be made whilst each vehicle is stationary, with and without the engine running to account for stead-state and dynamic conditions.

6.2 Vehicle ventilation

A range of vehicle ventilation conditions will be used during the sampling. These include the use of the passenger compartment ventilation fan set at, for example, 0%, 50%, and 100% of the maximum speed, open/closed windows, and the use of air conditioning. A key test condition will be the air recirculating setting, as AERs can be significantly reduced with recirculation switched on. As requested in the brief, we will also evaluate the purging effect of opening windows following tunnel transit.

A list of vehicle ventilation settings will be agreed with the Working Group prior to the measurement campaign. An example is shown in **Table 6-1**. Minimum numbers of test runs for each condition – taking into account the likely range of traffic conditions - will be determined. The emphasis will be on testing the effects of air recirculation (settings **S01**, **S02** and **S03, Table 6-1**). Note that setting **S03** aims to investigate the effects of turning the ventilation system from re-circulate to flow-through following tunnel transit. Setting **S04** will investigate the effect of having air recirculating settings turned off. During the initial testing phase, some runs will investigate the effect of having constant ventilation settings during the entire multi-tunnel transect, and compare these results to flushing air by opening car windows following tunnel transit.

Table 6-1: Provisional vehicle ventilation settings

Setting[a]	Windows	Air re-circulation	Air conditioning	Fan speed
S01	Closed[a]	On	On[b]	50%
S02		On	Off	50%
S03		On/Off[c]	Off	50%
S04		Off	Off	50%

(a) Initial tests will investigate the effects of opening the vehicle windows following tunnel transit. This is likely to result in the rapid equalisation of internal and external NO_2 concentrations.

(b) Some initial screening tests will be conducted to determine whether the air conditioning has any effect on AERs and in-vehicle NO_2.

(c) This will investigate the effect of turning the ventilation system from re-circulate to flow through following tunnel transit.

6.3 Number of runs and schedule

Note on number of runs per vehicle

One of the reviewers commented that the number of passes through the tunnels needs to be justified with a statistical power calculation.

We appreciate the desire for statistical rigour. However, it is uncommon to apply statistical power calculations to this type of study. These calculations are generally used to determine how many subjects required to detect an effect or difference between groups in health studies. The objective of the study is not to determine significant differences between on-road and in-vehicle concentrations, it is rather to measure AERs and NO_2 for local vehicles in order to test (and adapt, if necessary) a simple existing model. Covering a broadly representative sample of cars in which the known predictors of AER vary (*e.g.* manufacturing, odometer reading) is at least as important as testing a large number of cars to satisfy a sample size calculation. In any case, such calculations will tend to result in large sample sizes that cannot be supported by the project budget and timescale.

Our approach will involve maximising the number of test passes in order to maximise the confidence in the test results, all within the time and budget constraints. We note that where AERs for different vehicles show very similar patterns, we can consider subjecting fewer vehicles to the NO_2 measurements, with a corresponding increase in the number of passes per vehicle.

Given the typical travel time on the proposed route, assuming a 12-hour working day and limited congestion, approximately 16 runs could be completed. In practice it is likely that 10 – 12 runs could be completed per full day. It is acknowledged that this will require multiple test drivers/passengers for WHS reasons, and we will ensure risks are appropriately managed through development of Safe Work Method Statements for the measurement campaign.

Each vehicle will be tested over a two-day period. The first half-day will be devoted to the AER measurements, and the remaining 1.5 days will be devoted to the NO_2 measurements. It is anticipated the total duration of the monitoring campaign will be no less than two full weeks (we have assumed 18 days), which should equate to around 150 (one-way) runs through each of the selected tunnels, although the total will be spread over serval vehicles. Given that multiple NO_2 measurements will be made in each tunnel, a large amount of data will be 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 is prioritised over achieving the total number of desired runs.

6.4 Log sheets

To complement the logged data, each passenger will be asked to complete a trip log sheet. This will include information such as:

- Adverse weather conditions (*e.g.* heavy rain, fog, snow, gales, *etc.*)
- Unusual traffic conditions (breakdowns, accidents, *etc.*)

From the logged data (date and time) the trips will be classified into peak, off-peak and weekend periods.

6.5 Data from tunnel operators

Tunnel characteristics will be taken into consideration in the design of the measurement campaign and the conditions to be included (*e.g.* free flowing traffic or congested traffic) and to account for factors such as the prevailing in-tunnel air quality.

Based on information already available to Pacific Environment, as well as any additional information that can be supplied by RMS, each tunnel will be characterised in terms of the following:

- Tunnel geometry (section lengths, gradients).
- Ventilation (air throughput and wind speed).
- Traffic (distributions of volume, composition and speed).
- In-tunnel pollution measurements, including an analysis of data.
- The ability of the tunnel operators to provide real-time data during the measurement campaign. Tunnel system data will be requested for the period of the monitoring campaign.

6.6 Provision of monitoring data

Summary data and basic statistics from the monitoring campaign will be provided to RMS in advance of the modelling work. This will include, for example, box and whisker plots of internal concentrations, external concentrations and I/O ratios.

7 MODEL VALIDATION, DEVELOPMENT AND APPLICATION

7.1 Model validation and development

7.1.1 AER model

By far the largest and most up-to-date vehicle AER model is that described by **Hudda *et al.* (2012; 2013)**. In this model a substantial proportion of the variability in the AER for a given vehicle (up to around 80%) can be captured using information that is easily obtained without the need for new AER measurements. This information includes vehicle age, vehicle speed, vehicle manufacturer, and ventilation settings. The predicted AERs can then in turn be used to estimate in-vehicle pollutant exposures. For the RMS study the AER model will be validated against the measurements on the vehicles spanning a range of ages to confirm its local applicability.

The AER model includes both recirculated and outdoor air ventilation settings.

The model equation for **recirculated air** is:

$$\ln(\mathrm{AER}) = 2.79 + (0.019 \times \mathrm{speed}) + \left[0.015 \times \mathrm{age} + 3.3 \times 10^{-3}\mathrm{age}^2\right] + \left[-0.023 \times \mathrm{vol} + 6.6 \times 10^{-5}\mathrm{vol}^2\right] + \mathrm{Manuf\ \ Adjustment}$$

Where:

age is vehicle age[i] in years

vol is vehicle cabin volume

The manufacturer's adjustment is -0.71 for German vehicles and -0.39 for Japanese vehicles. If the speed is zero a -0.51 factor should be added.

The model equation for **outdoor air intake** is:

$$\ln(\mathrm{AER}) = 4.20 + \left[(1.88 \times \mathrm{fan\ \ strength}) + \left(-0.92 \times \mathrm{fan\ \ strength}^2\right)\right] + (0.0048 \times \mathrm{speed}) + (-0.0073 \times \mathrm{vol})$$

Where:

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

The coefficients for fan strength and fan strength^2 should be 0.40 and 0.13, respectively, at zero speed, and the speed term should be -0.32 at zero speed.

Figure 7-1 shows examples of the model predictions plotted against the two most significant determinants of AER under outdoor air conditions; ventilation fan strength and vehicle speed, for a 'sub-compact' and 'large sedan' vehicle, thus capturing the full range of AERs that can be expected under outdoor air intake conditions.

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

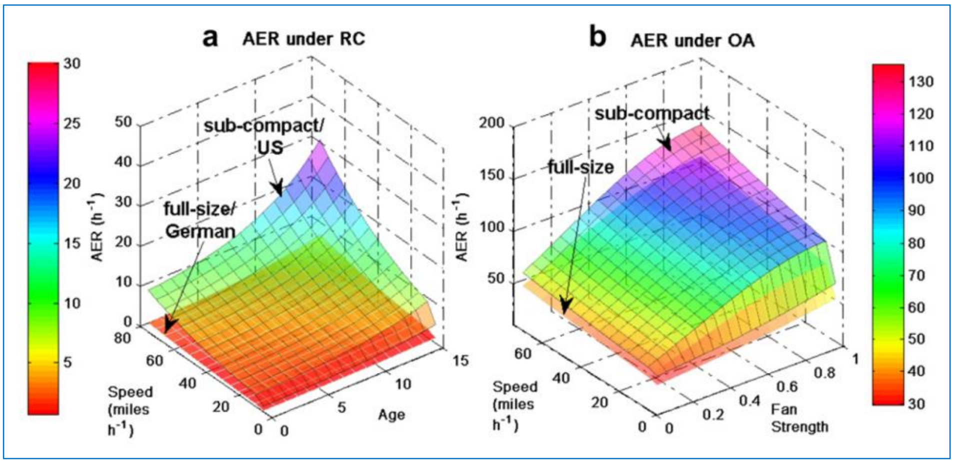

Figure 7-1. Predicted AER under recirculate (RC) and outdoor air (OA) intake settings as a function of the most significant determinant variables (Hudda *et al.*, 2012)

Hudda *et al.* (2012) state that these models had good fit and are likely to have a similar ability to predict AER in different datasets. However, it is important to understand how applicable the models will be to the future vehicle fleet in Sydney. Assuming that the models can be validated for the test vehicles in Sydney, it is unlikely that there will be significant technological changes in vehicles between 2015 and 2021, and a new vehicle model in 2015 can probably be assumed to be equivalent to a new model in 2021. Any work beyond this, such as projecting improvements in vehicle design, will be rather uncertain and beyond the scope of the RMS study.

7.1.2 I/O ratio model for NO_2

Most modelling of vehicle I/O ratios has focused on UFPs. However, generic mass-balance models that been used successfully to predict in-vehicle tunnel trip 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 will be adapted to predict NO_2 with some minor modifications. This approach has been employed in indoor air quality modelling for many years. **Knibbs *et al.* (2010)** successfully adapted from the indoor context to predict in-vehicle ultrafine particle concentrations during trips through the M5 East tunnel and is considered suitable for modelling NO_2.

<u>Model form</u>

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:

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

Equation 1

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)

The modelled and measured concentrations are shown in **Figure 7-4**.

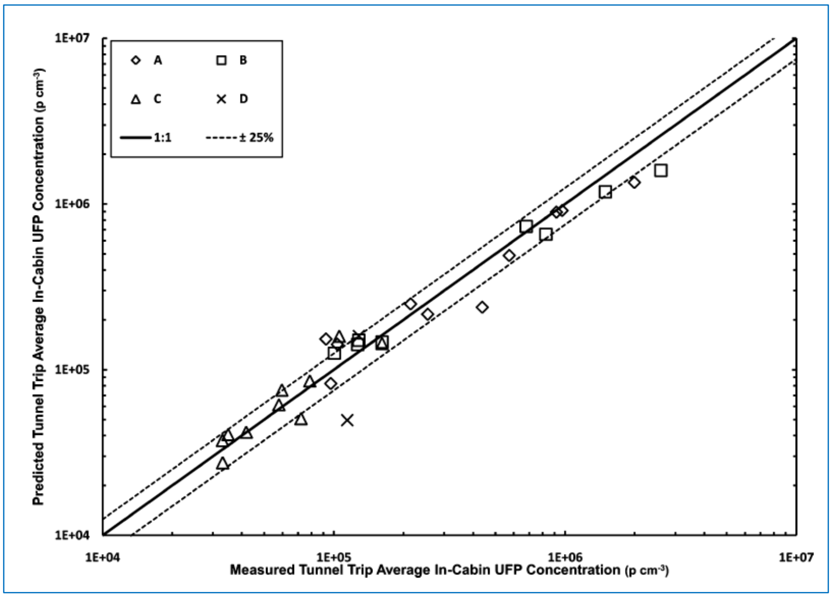

Figure 7-2: Measured and model-predicted in-cabin tunnel trip average UFP concentration (Knibbs *et al.*, 2010). A, B, C and D refer to different ventilation settings.

Many of the parameters in the full form of the model are not required when modelling vehicle cabins, and the model reduces to a much simpler form. Key parameters are the on-road concentration (which will show an increasing near-linear gradient with distance into a tunnel), the AER, the cabin volume and the duration of exposure. Cabin volume can be determined with sophisticated tracer gas methods but, manual measurement gives results that are comparable **(Ott *et al.*, 2008).**

Pooling data from **Knibbs *et al.* (2010)** and **Hudda *et al.* (2011)** to generate the largest dataset of passenger vehicle I/O ratios, **Hudda *et al.* (2012)** found that up to 79% of the variability in the I/O ratio could be explained on the basis of the same variables that explain AER (**Figure 7-3**). They were then able to combine this model with on-road concentration data to generate distributions of in-cabin concentrations to which commuters on different types of road would be exposed (**Figure 7-4**).

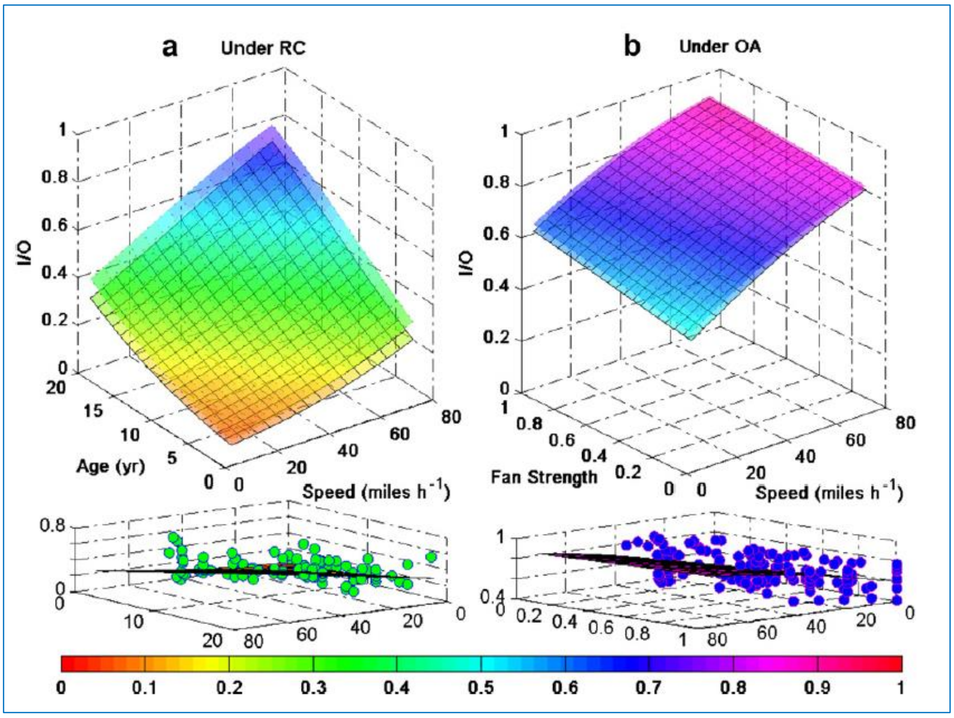

Figure 7-3: Predicted I/O ratios for ultrafine particles under recirculate (RC) and outdoor air (OA) intake settings as a function of the most significant determinant variables (Hudda *et al.*, 2012)

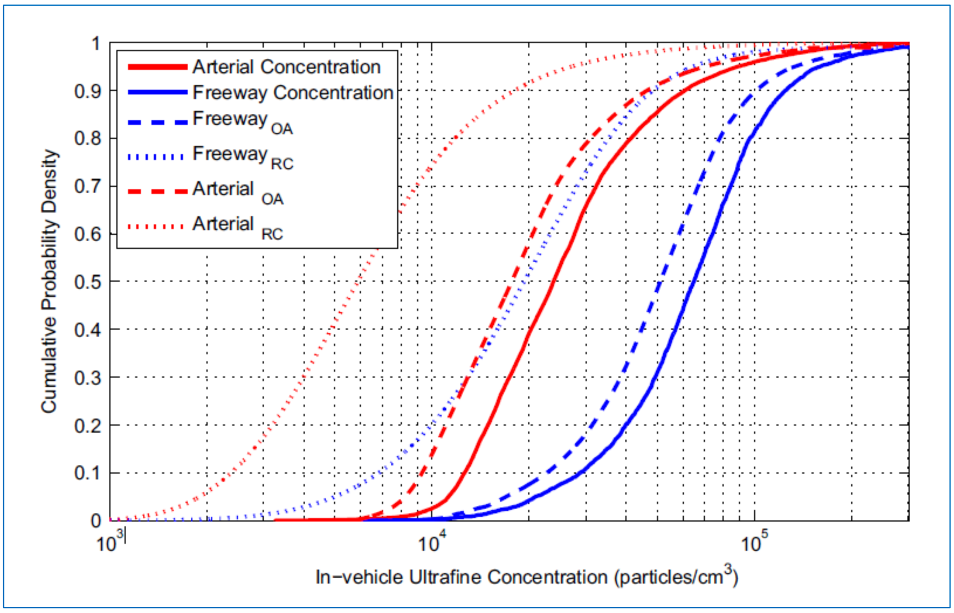

Figure 7-4: Expected in-cabin concentration for US vehicle fleet travelling on Los Angeles arterial roads and freeways under recirculate (RC) and outdoor air (OA) intake settings (Hudda *et al.*, 2012)

<u>NO_2 deposition</u>

It was noted in the literature review that deposition and reactions with indoor surfaces lead to NO_2 losses that can be comparable in magnitude to the effects when air exchange is low. The effects of such losses will be incorporated into the model as a loss term. NO_2 deposition losses in a vehicle cabin are exceedingly difficult to measure under field conditions, and the measurement of these is outside the scope of the project. However, they can be reliably estimated from the relationship between measured cabin surface to volume ratio and the deposition velocity of NO_2 in the literature. The sensitivity of predicted concentrations to the inclusion of an NO_2 loss parameter will be assessed by comparing predictions with it included and omitted.

Model assessment

The observed mean internal NO_2 levels calculated from the time series will be compared with the model prediction to assess their percent agreement. If they match the model will be deemed to be validated. If the results are discordant, then the measured AERs will be used to build the simple predictive model. The model's sensitivity to deposition will also be assessed.

7.2 Model application

Given an on-road NO_2 concentration the average in-vehicle concentration for a specified trip length can be estimated. The combined AER and I/O ratio model will be applied to the traffic and environment (NO_2 profile) in Sydney tunnels to determine a distribution of in-vehicle exposures. For example, the model will be used determine in-vehicle NO_2 concentrations for a range of vehicle types associated with external concentrations. Given the time constraints, it is likely that this will focus on a small, random sample of vehicles (not the models tested) to represent the Sydney fleet. 'Typical' I/O ratios will be determined to confirm (or otherwise) the conservatism that is inherent in in-tunnel NO_2 concentration limits.

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APPENDIX A: RESPONSE TO COMMENTS FROM REVIEWERS

A.1 COMMENTS FROM REVIEWER 1

Vehicle type

- Good discussion but no commitment to vehicle types or finalising source of vehicles

Pacific Environment: We have now committed to a much more specific list. More information is now provided for vehicle sources (staff, hire, share).

- It seems odd that there are only two small cars when these are more common in the fleet and there are multiple small cars in the staff cars that would be appropriate. Would not three small cars be more appropriate?

Pacific Environment: Agreed. We now have three small cars in the matrix.

Monitoring

- It would be good to add in the particulate matter monitoring equipment that will be used, even if it is not addressed elsewhere, so that EAC can comment on this. Even if this is provided separately to allow EAC to comment on this also.

Pacific Environment: A separate proposal has been provided.

- There needs to be additional information on the analysis of data (not just that an ANOVA may be performed).

Pacific Environment: Please see response below.

- There needs to be additional information on how windows up and windows down on exiting the tunnel will be assessed. For example I did not find information on the proportion of tunnel transits that will have windows up on exit or windows down and how any effect will be assessed.

Pacific Environment: Please see response below.

AER

- The speed limit of all tunnels is 80kph (or perhaps lower, and never 100kph). Is the data point of 100kph needed for some reason? Should one of 80kph be included?

Pacific Environment: It's a fair point. The idea here is to obtain data for speeds that are both achievable on public roads (low speeds are difficult) and have some separation. Based on previous tests on Australian cars we observed a linear increase in AER with speed. So, by covering as wide a range of speeds as possible, we avoid out-of-sample estimation of AER at higher speeds (which makes the data applicable to more driving scenarios; e.g. whether tunnel or otherwise, now or in the future). We would therefore prefer to include 100 km/h to address the wider applicability of the model across road types, and interpolate for 80 km/h. In the previous work we also found that 3 speeds (including stationary) was sufficient and offered the best compromise between practicality and accuracy.

Overall issues that need to be addressed

- **The number of passes through the tunnels needs to be justified with a statistical power calculation.**

Pacific Environment: It is uncommon to apply statistical power calculations to this type of study. These calculations are generally used to determine how many subjects required to detect an effect or difference between groups in health studies. It is unclear to us how this is relevant to the objectives of the study, which is not to determine significant differences between on-road and in-vehicle concentrations, but rather to measure AERs and NO_2 for local vehicles in order to test (and adapt, if necessary) a simple existing model.

If sample size calculations were to be conducted, they would need to address:

- The size of the vehicle population, and hence the number of test vehicles.
- The number of measurements (number of runs) per vehicle. Consideration would also need to be given to operational conditions.

Covering a broadly representative sample of cars in which the known predictors of AER vary (e.g. manufacturer, cabin volume) is more important than testing a large number of cars to satisfy a sample size calculation. In any case, such calculations will tend to result in large sample sizes that cannot be supported by the project budget and timescale.

- **There needs to be additional information on the analysis of data (not just that an ANOVA may be performed).**

Pacific Environment: The methodology states that ANOVA could be used. However, as stated above, this is not the primary objective. The primary purpose of the measurements would be model validation and therefore most of the statistical analysis would focus on descriptive and simple analytical statistics. This applies to both AER and NO_2 measurements. The NO_2 measurements will be obtained for short averaging periods (probably of the order of 10 seconds), and some examples of relationships and statistics that can be explored have been added to the report.

- **There needs to be additional information on how windows up and windows down on exiting the tunnel will be assessed.**

Pacific Environment: This will result in the rapid equalisation of internal and external concentrations, and will show up in the direct measurements.

- **Finalising the car vehicle types.**

Pacific Environment: In progress. We are currently assessing vehicle availability and OBD compliance.

- **Finalising NO_2 testing equipment.**

Pacific Environment: An order for two CAPS NO_2 analysers has been placed with Aerodyne in the US. Two LI-COR CO_2 monitors have also been purchased.

A.2 COMMENTS FROM REVIEWER 2

Overview

- I generally have a high level of confidence in the proposed work. In particular I find the instrumentation selected as first choice to be suitable and the scale and scope to be broadly appropriate.
- The study design as presented has some vagueness around analysis, modelling and outputs. Understanding the analysis envisaged is crucial to being able to assess the suitability of the proposed data capture method in detail.
- At present, I feel the major risk inherent in the study design is redundancy in some areas and lack of robustness in others. This could be addressed through greater clarity over analytical plans, or adjustment if the fieldwork design.
- Some points of clarification are requested, and some alterations to the study design are suggested below.

The proposed method in brief, as I understand it:

- Please let me know if I have misunderstood any part of the design.
- Representative vehicles will be selected.
- Their air exchange rates (AER) will be measured using the CO2 method used by Fruin et al. under a limited range of conditions, and **in recirculation model only** (page 13). The amount of time required to do this has not been specified in the design.

Pacific Environment: This seems to be a misinterpretation; we will be investigating AERs under both (i) re-circulation mode and (ii) fresh outside conditions. We propose, for each vehicle, 0.5 days for AER measurements and 1.5 days for NO_2 measurements. These time periods are constrained by the project timescale.

- AERs will be estimated using the model of Hudda et al.
- The estimated and observed results will be compared. If they match the model will be deemed to be "validated". It is unclear what is planned if they do not match.

Pacific Environment: If the results are discordant, then the measured AERs will be used to build the simple predictive model. The objectives of the project only require that a model relating AER, in-tunnel and in-cabin levels be developed. However, given our previous involvement with the Hudda et al model, we aim to deliver additional value-added information on whether this model can be applied to the Australia context in its current form, as this would be a useful tool for future assessments. If this proves not to be the case then we will revert to addressing the key objectives as described above.

- Drive the selected vehicles through the tunnels. The design suggests 15 vehicles with 6 different ventilation settings, giving 90 combinations. If each combination were used (which is not specified in the design) there would be only 1 or 2 tunnel transect per combination.

Pacific Environment: There are tight time constraints on the study, and only one set of monitoring equipment. The vehicles must therefore be tested in series. In the original version of the vehicle matrix we had 8 vehicles. We are now proposing to use 9. Some of the AC ventilation modes will be redundant, and can be reduced to 4 (possibly fewer), especially if the early tests show little difference between fan settings. This means that we could achieve 5 or 6 runs per fan setting. It should also be noted that each run includes multiple tunnels.

- Use observed external NO2 time series and observed AER for the vehicle as inputs to model of Knibbs et al to predict internal NO2 time series.

- What happens next is not discussed, so I can only assume that the observed time series (raw or aggregated) are compared to the modelled. Correcting for deposition losses is mentioned but it is unclear how this will be done. One approach might be to adjust a deposition term so as to improve model fit.

Pacific Environment: This is correct. The observed mean internal levels calculated from the time series will be compared with the model prediction to assess their percent agreement. The model's sensitivity to deposition will be assessed. Deposition is hard to measure in an occupied moving car, and this is outside the scope of the project. However, as detailed in the literature review, we can estimate the deposition parameter based on the surface/volume ratio of the cabin and the deposition velocity of NO_2 from the literature.

- The resulting model might then be considered to be "validated" and can be used to extrapolate results across the Sydney fleet.

Pacific Environment: This is correct. As noted in the methodology report, the model will be used to estimate the exposure of vehicle occupants to NO_2 based on the wider fleet characteristics and operational modes. We will provide 'typical' I/O ratios to confirm (or otherwise) the conservatism that is inherent in in-tunnel NO_2 concentration limits.

Strengths of the method

- I endorse a method which seeks to provide not just direct observational evidence, but also inform a modelling approach. The modelling will allow estimates for vehicles or settings beyond those observed to be estimated, allows for a fuller exploration of exposure outcomes and will be informative for tunnel exposure management and exposure assessment in general.

Pacific Environment: Noted.

Possible weaknesses of the method and suggested remedies

- Method
  - If I have understood the method correctly it allows each vehicle-ventilation combination to be sampled only once or twice. Given the high degree of variability in air quality in the tunnels (and speed in some cases) the risk of any single run being atypical, and the data being potentially misleading, is high.

Pacific Environment: Please refer to the earlier response.

  - I am not convinced that tunnel drive-throughs for all 15 vehicles is necessary. If two vehicles have a similar AER I believe there is little to be gained in testing them both.

Pacific Environment: We currently have 9 vehicles in the matrix. We can't know beforehand whether the vehicles will have similar AERs, but we can consider adapting the NO_2 measurement part of the campaign if this occurs.

  - A suggested solution is to reduce the number of vehicles used in the drive-throughs thus increasing the number of transects per vehicle-ventilation combination. This provides repeatability of results whilst also indicating the range of variability. I suggest that the vehicles driven through the tunnels are a sub-set of those tested for AER, based on the AER results. The sub-set could be selected to include vehicles with high, medium and low "baseline" AERs (baseline here meaning without intervention, i.e. open vents, high fan speed).

- This combination is intended to straddle the range of likely AERs in the fleet, but also indicate the degree of improvement achievable (a key project objective). Alternative vehicles and settings can be modelled.

- **Pacific Environment:** Please refer to the earlier response. We will retain this suggestion as an option.

  - Another way of addressing repeatability is to equip each car with a forward-facing video camera, perhaps set up to capture images every second. This will help to identify gross emitting vehicles which may produce atypically high external concentrations at low cost/effort.

Pacific Environment: We agree, and we had actually been discussing this internally. We will be fitting each vehicle with a video camera. The variance will be averaged out by multiple repeats, but the video information could be useful to explain unusually high spikes in NO_2. Additionally, this information might be used to correct potential bias if experiment times were to occur during periods when, for example, trucks comprise higher proportion of fleet. It is worth adding that the vehicle in front of the test vehicle should have a proportionally lower impact on the measurements with distance into a tunnel.

- The I/O ratio is dependent upon the internal and external concentrations as the vehicle enters the tunnel. Analysis will be simplified considerably if they are approximately equal, or at least that the internal concentration is stable. This is most simply achieved by flushing the vehicle cabin of pollutants after each tunnel has been exited. This is most efficiently achieved by opening windows. However, it will also be highly informative to keep ventilation settings constant during the entire multi-tunnel transect on a few runs. I recommend this is included if the matrix allows.

Pacific Environment: This should be straightforward to implement. We propose an initial (one-day) test period in which different effects can be investigated prior to the campaign.

- I do not understand why it would be proposed to measure AERs on recirculation mode only. How does this permit validation of the model of AERs for "open-vent" modes?

Pacific Environment: As noted earlier, this just seems to be a misinterpretation. We will be investigating AERs under re-circulation and 'outside air' conditions.

- Adding a deposition term will be easier if a non-depositing species (CO, CO2?) is also measured and observed.

Pacific Environment: We appreciate the thoroughness but as this is not a full-scale research project and we are under significant time constraints a detailed investigation on the rate of NO_2 deposition will not be possible. We will therefore rely on cabin surface volume and the deposition velocity of NO_2 from the literature. Deposition is unlikely to be a major factor affecting NO_2 levels under the conditions we will test (as opposed to residential indoor environments where it can be important). Nonetheless, we will assess the sensitivity of our results to estimated deposition rates.

<u>Analysis</u>

- Analysis consists of two major activities: 1) generating statistics describing the observed data, 2) results of the modelling activities. The former is relatively simple, whereas the latter is more complex. I recommend that the basic statistics from the observations can be completed and released in advance of the modelling.

Pacific Environment: Noted.

- The statistics to be generated are not discussed. It should be noted that even for the same vehicle with the same ventilation setting, I/O ratio is likely to vary due to random encounters with other vehicles, variation in baseline concentrations (i.e. brought into the tunnel, traffic speed and tunnel length. The latter point is because there may not be sufficient time for an equilibrium to be achieved. This is especially so in the M5 East where the ventilation system means that a gradually rising or even concentration profile is **not** expected. The project team need to appreciate that the work of Hudda et al linking I/O ratio (or concentrations) to AER is based on much longer non-tunnel journeys during which concentrations remain much closer to equilibrium than is the case in tunnels (which represent a large perturbation away from equilibrium).

Pacific Environment: In our experience it is not unusual for equilibrium to be reached under tunnel conditions (even in the M5 East) and for a variety of recirculated and fresh air settings. This is underscored by the fact that when Hudda's open road, relatively long duration ultrafine I/O data were combined with Knibbs' data collected in the M5 East, the two data sets were statistically indistinguishable. The Hudda et al. model is for ultrafine particles, and the simple model we propose to relate AER and NO_2 is a basic mass-balance model that is aimed at addressing the objective of using a simple approach to relate AER, on-road and in-cabin levels.

It is also worth repeating that each trip will include multiple tunnels, and NO_2 measurements will be made using fast-response instruments that will generate a large amount of data under a wide range of external concentrations and real-world exposure conditions.

- Consequently, multiple repeats of the same vehicle-ventilation combination is recommended to indicate this variability. Thus, I recommend as a minimum that observational data is presented as box plots of average internal concentrations, average external concentrations and I/O ratios for each individual tunnel for each nominal AER represented.

Pacific Environment: Noted.

Further points and queries

- Has the accuracy of the GPS been assessed along the route chosen, especially around the Eastern Distributor which is surrounded by buildings?

Pacific Environment: We are currently in the process of field testing two GPS alternative systems (use of mobile phone with GPS tracking software and a field GPS logger). The mobile phone data has proven to be a reliable and accurate source of GPS data. The OBD output will be used to provide vehicle speed and location (via speed) in the absence of a GPS signal.

- The design makes no mention of the use of tunnel systems data. I would suggest that it would be useful to compare external data captured with data from the LCT in particular. However, I recognise that this might be considered part of a separate project (e.g. implementation of new NO2 guideline).

Pacific Environment: This is actually an omission. It was included in the original proposal but has been left out of the methodology report unintentionally. We will put it back in. In addition, a request has been sent to RMS for the tunnel characteristics and confirmation of the willingness of the tunnel operators to provide data during the measurement campaign.

- The data captured in this project will have substantial value for additional air quality research. For example, NO2 levels on major roads (as opposed to alongside) are largely unknown. I suggest that options to facilitate further research and data-mining are considered by RMS.

Pacific Environment: All measured data are the property of RMS, so options for this can be explored.

- It may be useful to know that I/O ratios greater than one might be observed. This could occur when a higher external concentration arises in an earlier stage of a tunnel transect, e.g. due to a gross emitter or ahead of an air extraction point. External concentrations may subsequently fall rapidly leaving a higher concentration trapped inside the vehicle pushing I/O above 1. This has regularly been observed by NIWA in non-tunnel environments.

Pacific Environment: Noted.

Appendix C PHOTO LOG

HOLDEN ASTRA WAGON (2008)

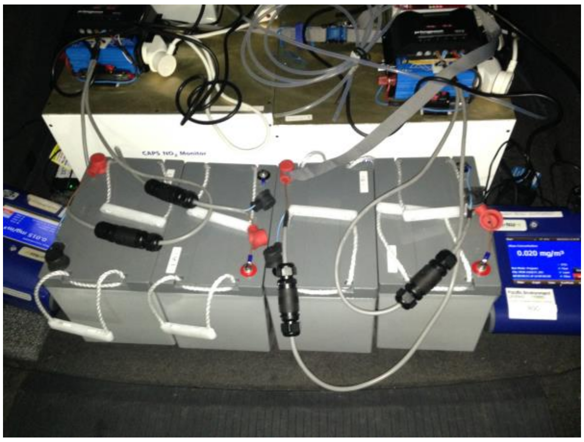

Figure C-1: Holden Astra set up with Instrumentation running (Bottom Half)

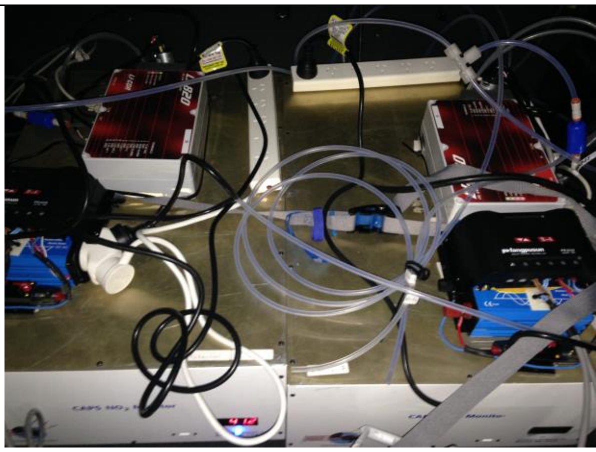

Figure C-2: Holden Astra set up with instrumentation running (Top Half)

Figure C-3: Holden Astra complete installation of equipment

BMW X3 SUV (2014)

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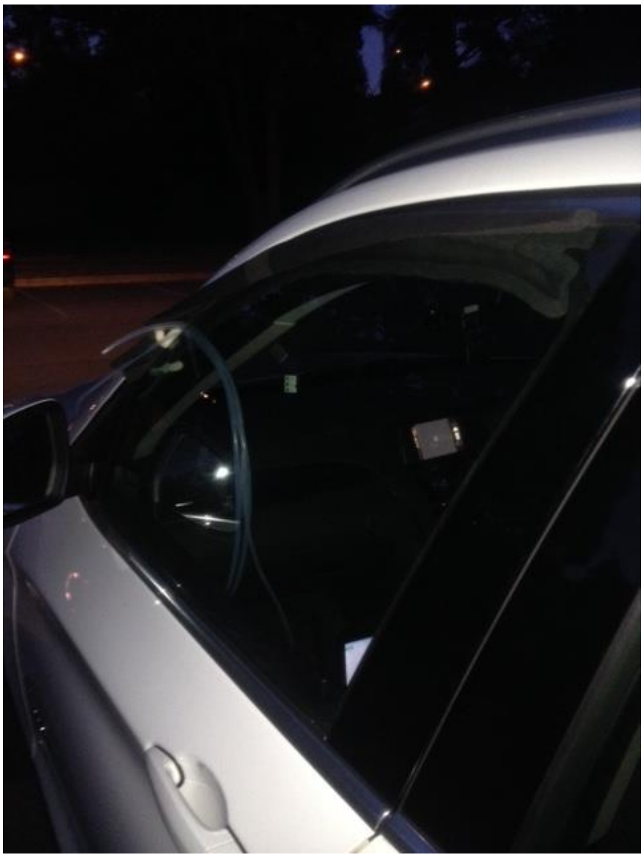
<td>
Figure C-4: BMW X3 SUV Tube Setup (Passenger Door)</td>
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Figure C-5: BMW X3 SUV complete setup of equipment</td>
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FORD FIESTA (2002)

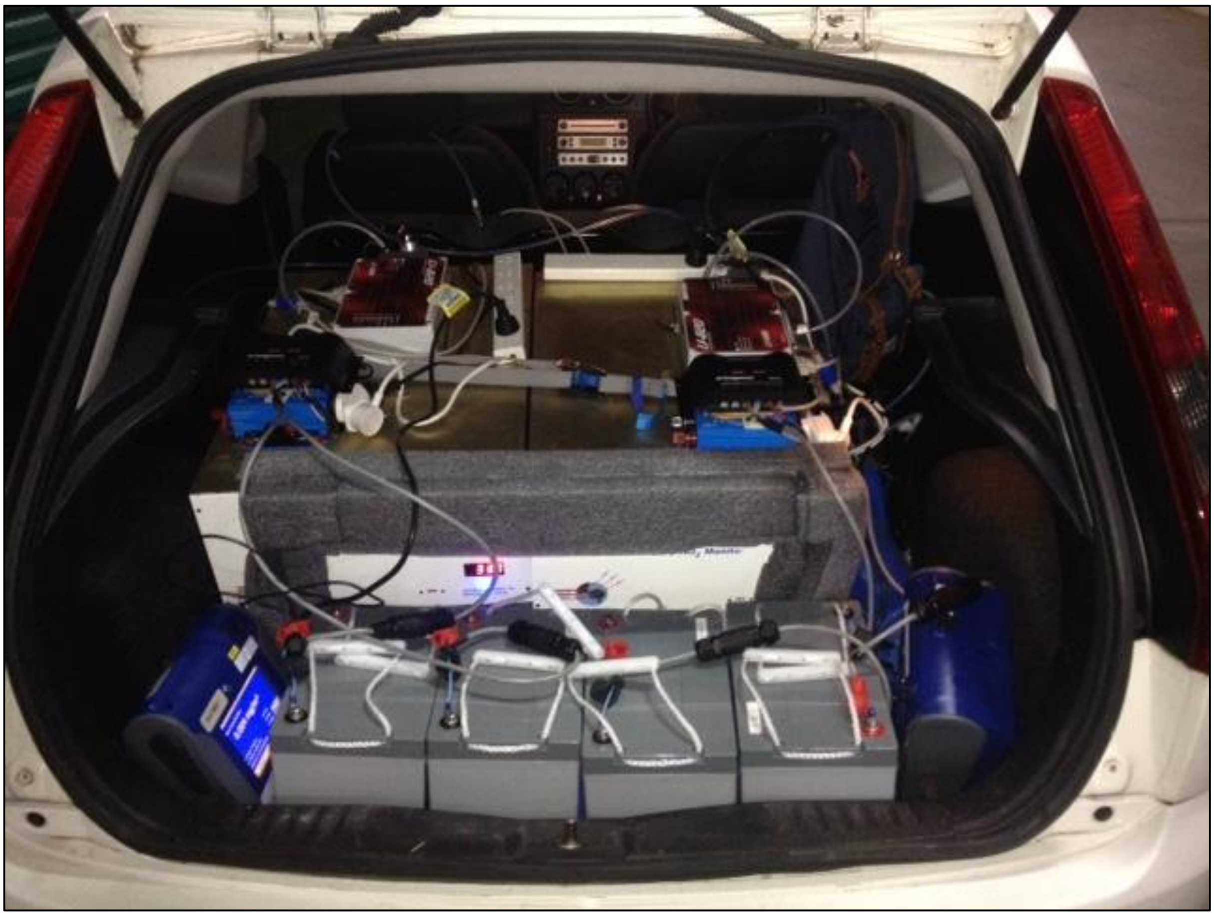


Figure C-6: Ford Fiesta Setup

FIAT PUNTO (2007)

Figure C-7: Fiat Front Passenger Tube Setup (back view)

Figure C-8: Fiat Front Passenger Tube Setup (Front view)

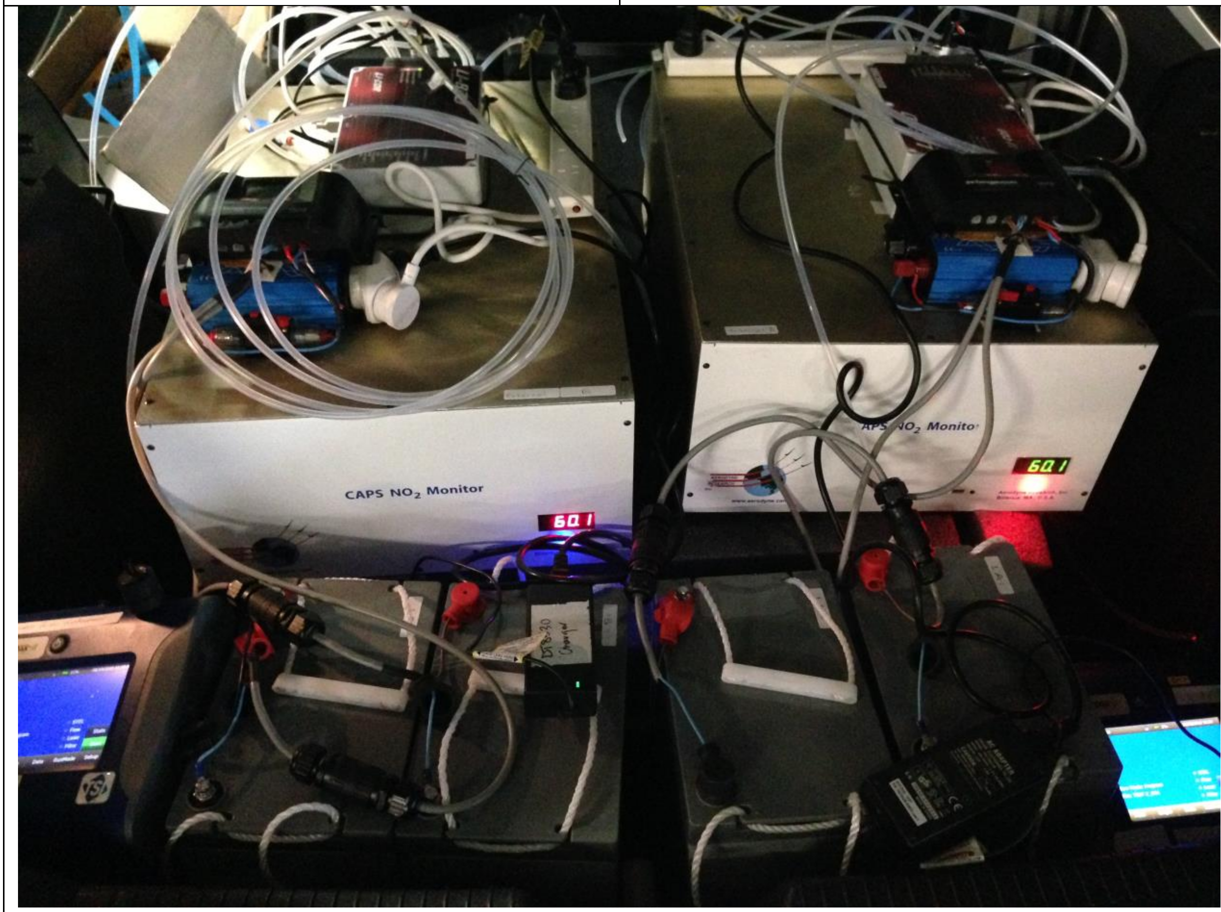


Figure C-9: Fiat Complete Setup

HYUNDAI I30

Figure C-10: Hyundai Passenger side Tube Setup

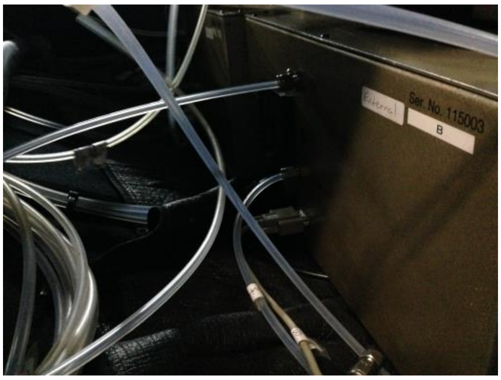


Figure C-11: Hyundai NO2 Cord Setup to NO2 Analyser

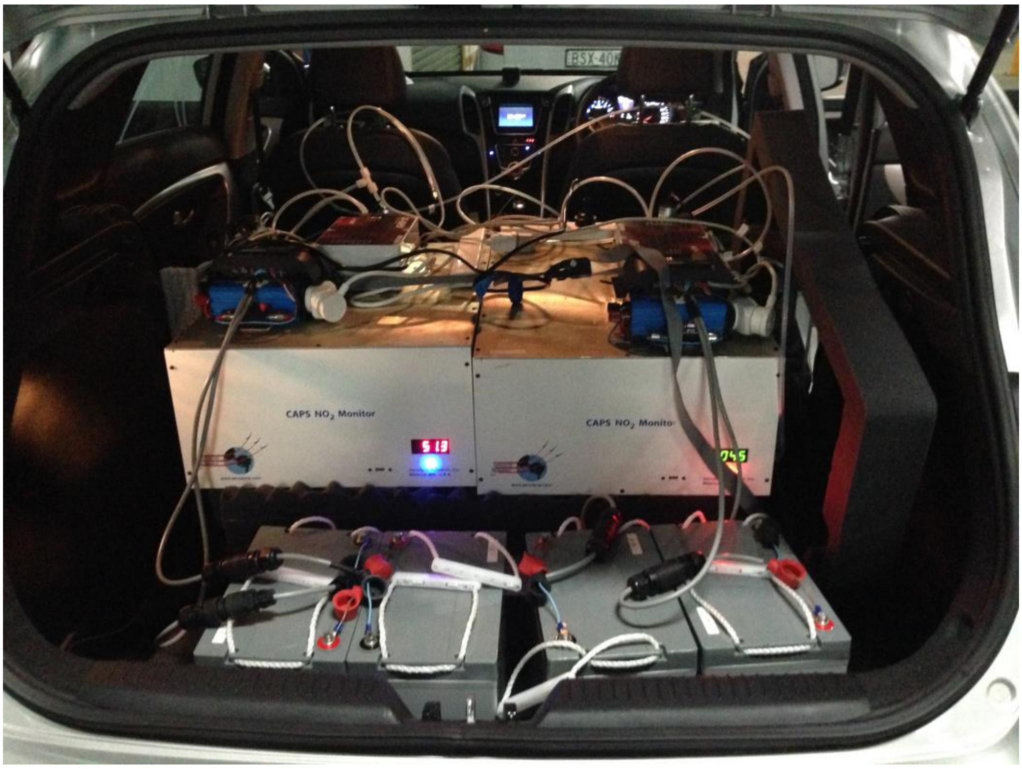


Figure C-12: Complete Setup of equipment

TOYOTA COROLLA (2008)

Figure C-13: Toyota Corolla drivers side tube setup

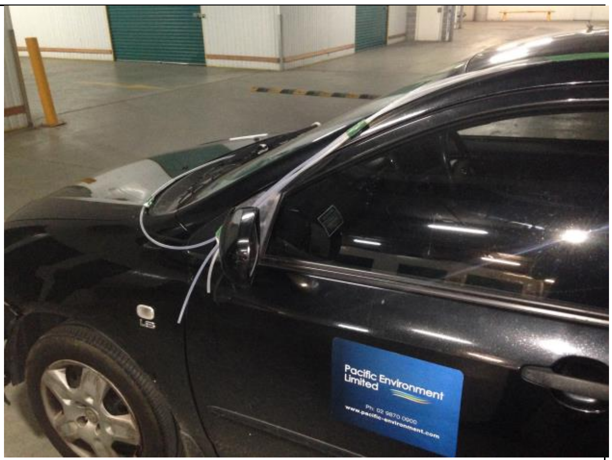


Figure C-14: Toyota Corolla passengers side tube setup

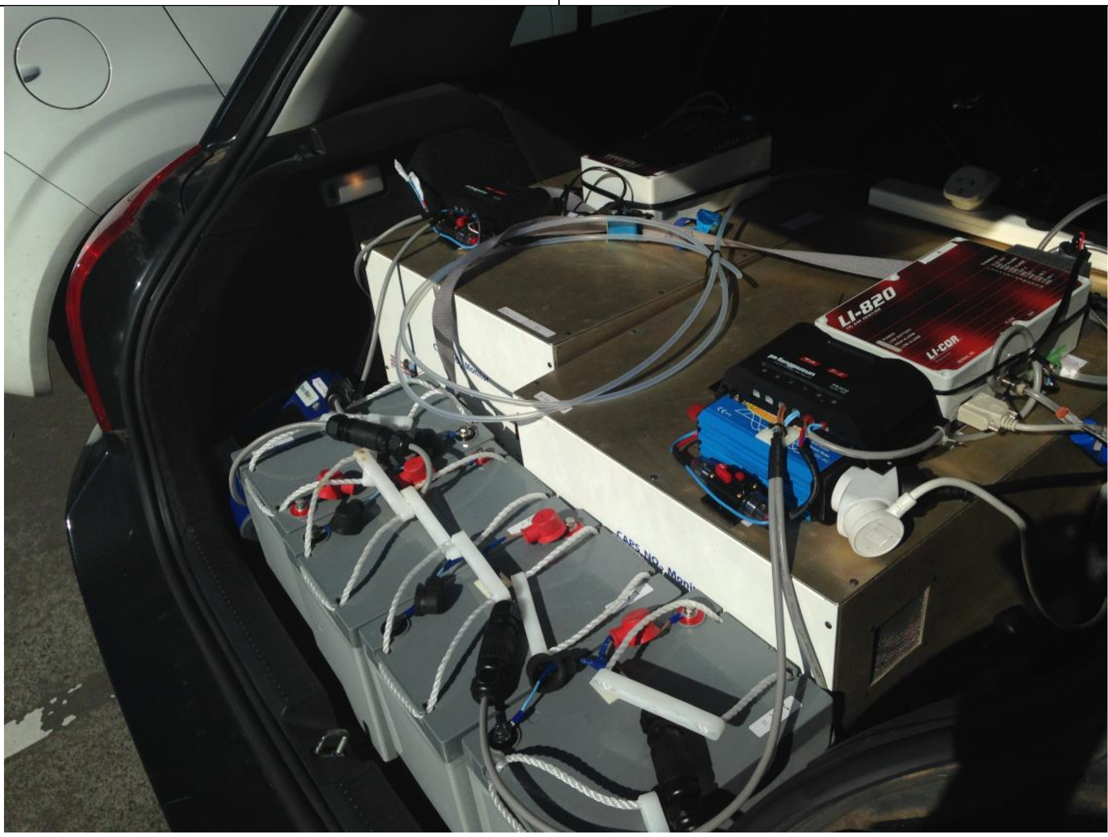


Figure C-15: Toyota Corolla Complete Setup

AUDI A3 (2002)

Figure C-16: Audi A3 complete setup

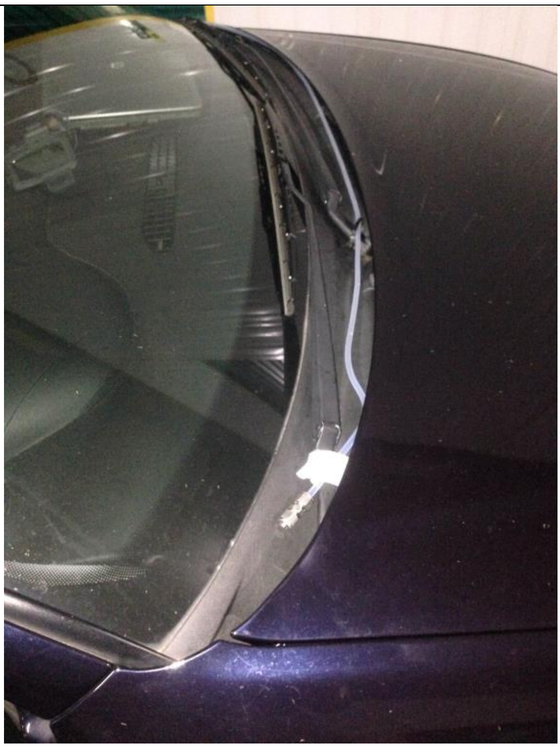


Figure C-17: Audi A3 external tube positioning

Figure C-18: Audi A3 GPS/speed monitoring and GoPro

SUBARU OUTBACK (2007)

Figure C-19: Subaru Outback Complete Setup

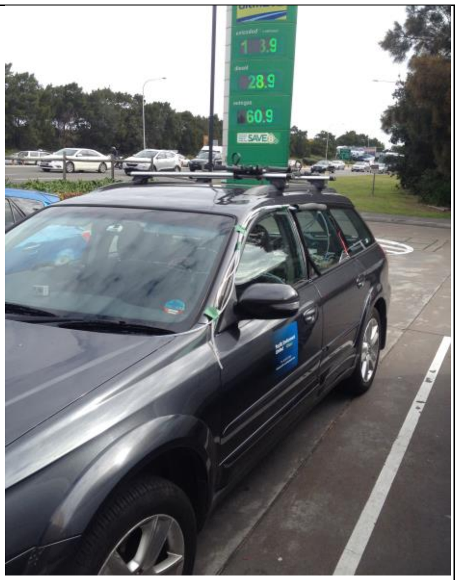


Figure C-20: Subaru Outback

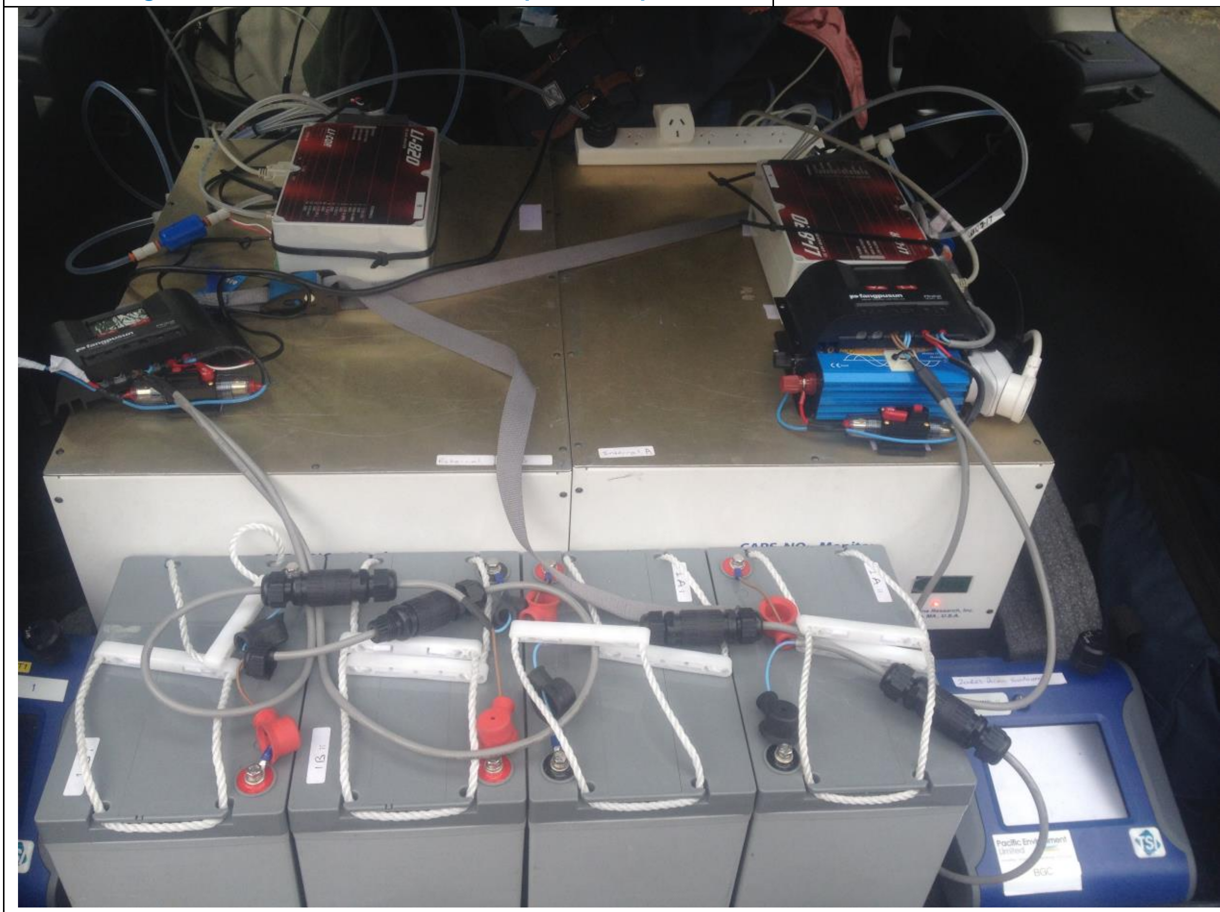


Figure C-21: Subaru Outback installed equipment

Appendix D SUMMARY TABLES

NITROGEN DIOXIDE

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
Car 1- Holden Astra Wagon (2008)			
EDMT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	73	57	**0.78**
25/08/2015 10:25	91	70	**0.77**
25/08/2015 19:45	55	43	**0.79**
MD5			
R-Off | AC-Off | Fn-0%	59	34	0.58
25/08/2015 15:45	42	32	**0.77**
25/08/2015 19:06	86	38	0.44
MD6			
R_Off | AC-Off | Fn-100%	136	129	**0.95**
25/08/2015 17:30	45	45	**1.00**
26/08/2015 9:29	143	135	**0.94**
MD2			
R-On | AC-Off | Fn-50%	*91*	*27*	*0.30*
25/08/2015 12:15	97	15	**0.15**
26/08/2015 11:45	86	36	0.42
South Bound			
MD4			
R-Off | AC-Off | Fn-50%	143	110	**0.77**
25/08/2015 16:41	51	101	**1.99**
25/08/2015 19:34	44	50	**1.12**
26/08/2015 8:15	213	138	0.65
MD5			
R-Off | AC-Off | Fn-0%	175	11	**0.06**
25/08/2015 9:22	175	11	**0.06**
MD6			
R_Off | AC-Off | Fn-100%	143	108	**0.75**
25/08/2015 11:34	143	108	**0.75**
MD2			
R-On | AC-Off | Fn-50%	85	12	**0.15**
25/08/2015 18:19	85	12	**0.15**
Lane Cove Tunnel			
East Bound			
MD4			
R-Off | AC-Off | Fn-50%	145	91	0.63

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
25/08/2015 16:25	186	101	0.54
25/08/2015 19:23	108	82	**0.76**
MD5			
R-Off | AC-Off | Fn-0%	221	34	**0.15**
25/08/2015 8:45	211	26	**0.12**
26/08/2015 7:56	233	44	**0.19**
MD6			
R_Off | AC-Off | Fn-100%	319	247	**0.78**
25/08/2015 11:23	319	247	**0.78**
MD2			
R-On | AC-Off | Fn-50%	168	14	**0.09**
25/08/2015 14:51	177	6	**0.04**
25/08/2015 18:07	153	16	**0.10**
26/08/2015 10:43	176	19	**0.11**
West Bound			
MD5			
R-Off | AC-Off | Fn-0%	82	32	0.39
25/08/2015 16:02	95	39	0.41
25/08/2015 19:16	54	32	0.58
26/08/2015 7:41	97	26	0.26
MD6			
R_Off | AC-Off | Fn-100%	97	88	**0.90**
25/08/2015 17:44	107	90	**0.85**
26/08/2015 10:03	84	85	**1.01**
MD2			
R-On | AC-Off | Fn-50%	97	20	0.21
25/08/2015 12:25	108	14	**0.13**
26/08/2015 11:54	84	27	0.32
M5 Tunnel			
East Bound			
MD4			
R-Off | AC-Off | Fn-50%	405	324	**0.80**
25/08/2015 9:59	378	297	**0.79**
25/08/2015 11:56	435	355	**0.82**
MD5			
R-Off | AC-Off | Fn-0%	285	68	0.24
25/08/2015 15:33	318	82	0.26
25/08/2015 18:45	254	55	0.22
MD6			
R_Off | AC-Off | Fn-100%	208	182	**0.88**

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
25/08/2015 17:17	279	246	**0.88**
26/08/2015 8:53	62	53	**0.85**
MD2			
R-On | AC-Off | Fn-50%	319	43	**0.13**
26/08/2015 11:29	319	43	**0.13**
West Bound			
MD4			
R-Off | AC-Off | Fn-50%	323	231	**0.72**
25/08/2015 17:02	289	210	**0.73**
26/08/2015 8:30	364	256	**0.70**
MD5			
R-Off | AC-Off | Fn-0%	314	28	**0.09**
25/08/2015 9:36	314	28	**0.09**
MD6			
R_Off | AC-Off | Fn-100%	377	315	**0.84**
25/08/2015 11:46	377	315	**0.84**
MD2			
R-On | AC-Off | Fn-50%	284	16	**0.06**
25/08/2015 15:19	339	12	**0.04**
25/08/2015 18:32	126	11	**0.09**
26/08/2015 11:08	409	32	**0.08**
SHT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	82	69	**0.85**
25/08/2015 10:28	117	89	**0.76**
25/08/2015 19:48	57	55	**0.97**
MD5			
R-Off | AC-Off | Fn-0%	79	39	0.49
25/08/2015 19:08	79	39	0.49
MD6			
R_Off | AC-Off | Fn-100%	109	110	**1.01**
25/08/2015 17:34	117	112	**0.96**
26/08/2015 9:57	79	102	**1.29**
MD2			
R-On | AC-Off | Fn-50%	146	21	**0.14**
25/08/2015 12:18	141	15	**0.10**
26/08/2015 11:48	154	30	**0.20**
South Bound			
MD4			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
R-Off | AC-Off | Fn-50%	51	41	**0.80**
25/08/2015 16:33	56	47	**0.84**
25/08/2015 19:31	30	35	**1.14**
26/08/2015 8:10	67	39	0.59
MD5			
R-Off | AC-Off | Fn-0%	16	2	**0.10**
25/08/2015 9:15	16	2	**0.10**
MD6			
R_Off | AC-Off | Fn-100%	54	44	**0.82**
25/08/2015 11:31	54	44	**0.82**
MD2			
R-On | AC-Off | Fn-50%	38	19	0.50
25/08/2015 14:58	71	11	**0.15**
25/08/2015 18:16	35	14	0.41
26/08/2015 10:50	21	27	**1.30**
Car 2 - Ford Fiesta			
EDMT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	149	123	**0.83**
26/08/2015 17:44	126	131	**1.04**
26/08/2015 19:32	83	33	0.39
27/08/2015 9:09	96	92	**0.95**
27/08/2015 17:51	189	151	**0.79**
MD2			
R-On | AC-Off | Fn-50%	116	48	0.41
27/08/2015 10:57	91	56	0.62
27/08/2015 15:14	141	40	0.28
South Bound			
MD5			
R-Off | AC-Off | Fn-0%	200	53	0.27
26/08/2015 16:46	105	46	0.43
27/08/2015 7:44	297	45	**0.15**
27/08/2015 14:27	224	83	0.37
MD6			
R_Off | AC-Off | Fn-100%	224	195	**0.87**
26/08/2015 18:50	141	131	**0.93**
27/08/2015 10:03	344	291	**0.85**
27/08/2015 16:12	169	150	**0.89**
LCT			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
East Bound			
MD5			
R-Off | AC-Off | Fn-0%	292	90	0.31
26/08/2015 16:23	263	118	0.45
27/08/2015 7:18	635	111	**0.18**
27/08/2015 11:35	198	55	0.28
27/08/2015 14:15	219	70	0.32
MD6			
R_Off | AC-Off | Fn-100%	271	204	**0.75**
26/08/2015 18:33	237	198	**0.84**
27/08/2015 9:52	316	218	0.69
27/08/2015 15:50	264	197	**0.75**
West Bound			
MD4			
R-Off | AC-Off | Fn-50%	100	79	**0.79**
26/08/2015 18:02	110	105	**0.96**
26/08/2015 19:41	62	32	0.52
27/08/2015 9:22	109	85	**0.78**
27/08/2015 18:09	118	93	**0.78**
MD5			
R-Off | AC-Off | Fn-0%	147	78	0.53
26/08/2015 16:09	147	78	0.53
MD2			
R-On | AC-Off | Fn-50%	91	47	0.51
27/08/2015 11:06	81	53	0.66
27/08/2015 15:26	100	40	0.40
M5T			
East Bound			
MD4			
R-Off | AC-Off | Fn-50%	301	214	**0.71**
26/08/2015 17:28	260	226	**0.87**
26/08/2015 19:18	191	49	0.26
27/08/2015 8:39	435	315	**0.72**
27/08/2015 17:04	278	223	**0.80**
MD2			
R-On | AC-Off | Fn-50%	426	65	**0.15**
27/08/2015 10:42	477	76	**0.16**
27/08/2015 15:00	364	52	**0.14**
West Bound			
MD5			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
R-Off | AC-Off | Fn-0%	360	63	**0.17**
26/08/2015 17:09	221	56	0.25
27/08/2015 7:59	350	58	**0.17**
27/08/2015 14:43	532	77	**0.14**
MD6			
R_Off | AC-Off | Fn-100%	246	216	**0.88**
26/08/2015 19:04	127	135	**1.06**
27/08/2015 10:19	332	282	**0.85**
27/08/2015 16:45	250	214	**0.86**
SHT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	144	125	**0.86**
26/08/2015 17:50	148	145	**0.98**
26/08/2015 19:35	92	33	0.37
27/08/2015 9:14	167	136	**0.81**
27/08/2015 18:00	144	134	**0.93**
MD2			
R-On | AC-Off | Fn-50%	172	49	0.28
27/08/2015 10:59	130	61	0.47
27/08/2015 15:18	203	41	**0.20**
South Bound			
MD5			
R-Off | AC-Off | Fn-0%	127	48	0.38
26/08/2015 16:33	156	52	0.33
27/08/2015 7:37	98	33	0.34
27/08/2015 14:24	68	63	**0.93**
MD6			
R_Off | AC-Off | Fn-100%	118	116	**0.98**
26/08/2015 18:43	95	106	**1.12**
27/08/2015 10:00	74	70	**0.94**
27/08/2015 16:00	141	133	**0.94**
Car 3 - BMW X3			
EDMT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	112	55	0.49
1/09/2015 9:36	133	70	0.53
1/09/2015 17:33	92	40	0.44
MD2			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
R-On | AC-Off | Fn-50%	121	21	**0.17**
1/09/2015 11:26	153	26	**0.17**
1/09/2015 19:21	87	16	**0.18**
South Bound			
MD5			
R-Off | AC-Off | Fn-0%	146	11	**0.08**
1/09/2015 16:17	146	11	**0.08**
MD6			
R_Off | AC-Off | Fn-100%	121	56	0.46
1/09/2015 10:32	147	46	0.31
1/09/2015 18:28	104	63	0.60
LCT			
East Bound			
MD5			
R-Off | AC-Off | Fn-0%	289	15	**0.05**
1/09/2015 7:59	274	1	**0.01**
1/09/2015 16:01	306	30	**0.10**
MD6			
R_Off | AC-Off | Fn-100%	270	98	0.36
1/09/2015 10:21	279	66	0.24
1/09/2015 18:16	261	134	0.51
West Bound			
MD4			
R-Off | AC-Off | Fn-50%	159	42	0.27
1/09/2015 9:46	149	56	0.38
1/09/2015 17:46	168	30	**0.18**
MD2			
R-On | AC-Off | Fn-50%	98	18	**0.18**
1/09/2015 11:35	120	22	**0.18**
1/09/2015 19:31	75	14	**0.18**
M5T			
East Bound			
MD4			
R-Off | AC-Off | Fn-50%	425	206	0.48
1/09/2015 9:16	462	290	0.63
1/09/2015 17:18	234	47	**0.20**
MD2			
R-On | AC-Off | Fn-50%	420	28	**0.07**
1/09/2015 11:11	482	19	**0.04**
1/09/2015 19:03	337	40	**0.12**

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
West Bound			
MD5			
R-Off | AC-Off | Fn-0%	307	7	**0.02**
1/09/2015 8:27	281	5	**0.02**
1/09/2015 16:49	323	8	**0.02**
MD6			
R_Off | AC-Off | Fn-100%	300	172	0.57
1/09/2015 10:45	445	139	0.31
1/09/2015 18:47	232	188	**0.81**
SHT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	138	48	0.35
1/09/2015 9:38	147	79	0.54
1/09/2015 17:37	131	27	0.20
MD2			
R-On | AC-Off | Fn-50%	202	20	**0.10**
1/09/2015 11:29	205	24	**0.12**
1/09/2015 19:24	199	15	**0.07**
South Bound			
MD5			
R-Off | AC-Off | Fn-0%	98	20	0.20
1/09/2015 16:09	98	20	0.20
MD6			
R_Off | AC-Off | Fn-100%	70	35	0.50
1/09/2015 10:29	82	31	0.37
1/09/2015 18:24	58	39	0.67
Car 4 - Hyundai i30			
EDMT			
North Bound			
MD5			
R-Off | AC-Off | Fn-0%	112	44	0.39
2/09/2015 13:26	105	46	0.44
3/09/2015 12:42	119	43	0.36
4/09/2015 12:19	111	43	0.39
MD6			
R_Off | AC-Off | Fn-100%	108	98	**0.90**
2/09/2015 15:27	100	86	**0.86**
3/09/2015 14:35	116	109	**0.94**
MD2			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
R-On | AC-Off | Fn-50%	133	13	**0.10**
4/09/2015 16:03	133	13	**0.10**
South Bound			
MD4			
R-Off | AC-Off | Fn-50%	172	63	0.37
2/09/2015 14:23	191	114	0.60
3/09/2015 13:32	176	110	0.63
4/09/2015 11:28	160	9	**0.06**
MD6			
R_Off | AC-Off | Fn-100%	194	148	**0.76**
4/09/2015 13:17	194	148	**0.76**
MD2			
R-On | AC-Off | Fn-50%	221	10	**0.05**
2/09/2015 12:46	239	9	**0.04**
3/09/2015 11:53	203	12	**0.06**
LCT			
East Bound			
MD4			
R-Off | AC-Off | Fn-50%	242	97	0.40
2/09/2015 14:12	225	133	0.59
3/09/2015 13:21	235	147	0.63
4/09/2015 11:17	269	6	**0.02**
MD6			
R_Off | AC-Off | Fn-100%	278	213	**0.77**
4/09/2015 13:06	278	213	**0.77**
MD2			
R-On | AC-Off | Fn-50%	259	16	**0.06**
2/09/2015 12:35	271	18	**0.07**
3/09/2015 11:42	247	15	**0.06**
West Bound			
MD5			
R-Off | AC-Off | Fn-0%	125	41	0.33
2/09/2015 13:36	146	46	0.32
3/09/2015 12:53	113	36	0.31
4/09/2015 12:29	116	40	0.35
MD6			
R_Off | AC-Off | Fn-100%	138	109	**0.79**
2/09/2015 15:38	139	112	**0.81**
3/09/2015 14:44	137	107	**0.78**
MD2			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
R-On | AC-Off | Fn-50%	120	10	**0.09**
2/09/2015 12:27	110	11	**0.10**
3/09/2015 10:33	114	2	**0.02**
4/09/2015 16:17	140	18	**0.13**
M5T			
East Bound			
MD5			
R-Off | AC-Off | Fn-0%	526	42	**0.08**
2/09/2015 13:12	495	60	**0.12**
3/09/2015 12:27	546	35	**0.06**
4/09/2015 12:05	537	32	**0.06**
MD6			
R_Off | AC-Off | Fn-100%	444	387	**0.87**
2/09/2015 14:56	410	353	**0.86**
3/09/2015 14:00	479	421	**0.88**
MD2			
R-On | AC-Off | Fn-50%	395	32	**0.08**
4/09/2015 15:18	395	32	**0.08**
West Bound			
MD4			
R-Off | AC-Off | Fn-50%	356	275	**0.77**
2/09/2015 14:38	384	286	**0.74**
3/09/2015 13:45	306	248	**0.81**
4/09/2015 11:42	382	294	**0.77**
MD6			
R_Off | AC-Off | Fn-100%	420	370	**0.88**
4/09/2015 13:32	420	370	**0.88**
MD2			
R-On | AC-Off | Fn-50%	415	7	**0.02**
2/09/2015 12:58	449	4	**0.01**
3/09/2015 12:05	378	10	**0.03**
SHT			
North Bound			
MD5			
R-Off | AC-Off | Fn-0%	141	51	0.37
2/09/2015 13:29	152	56	0.37
3/09/2015 12:45	149	49	0.33
4/09/2015 12:22	124	51	0.41
MD6			
R_Off | AC-Off | Fn-100%	186	154	**0.82**

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
2/09/2015 15:30	180	154	**0.85**
3/09/2015 14:37	195	153	**0.79**
MD2			
R-On | AC-Off | Fn-50%	206	12	**0.06**
4/09/2015 16:09	206	12	**0.06**
South Bound			
MD4			
R-Off | AC-Off | Fn-50%	66	38	0.58
2/09/2015 14:20	82	54	0.65
3/09/2015 13:28	59	46	**0.78**
4/09/2015 11:25	53	12	0.23
MD6			
R_Off | AC-Off | Fn-100%	75	58	**0.76**
4/09/2015 13:14	75	58	**0.76**
MD2			
R-On | AC-Off | Fn-50%	54	12	0.23
2/09/2015 12:43	56	11	**0.20**
3/09/2015 11:49	53	14	0.26
Car 5 - Audi A3			
EDMT			
North Bound			
MD1			
R-On | AC-On | Fn-50%	125	63	0.50
9/09/2015 11:41	127	57	0.45
8/09/2015 9:21	122	66	0.54
8/09/2015 12:12	126	64	0.51
MD4			
R-Off | AC-Off | Fn-50%	116	42	0.37
8/09/2015 18:14	94	34	0.37
9/09/2015 8:59	135	49	0.36
MD2			
R-On | AC-Off | Fn-50%	167	45	0.27
8/09/2015 16:20	167	45	0.27
MD3			
R-OnOff | AC-Off | Fn-50%	112	51	0.45
9/09/2015 10:37	115	42	0.37
8/09/2015 10:47	109	61	0.56
South Bound			
MD1			
R-On | AC-On | Fn-50%	169	38	0.23

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
8/09/2015 14:49	166	43	0.26
9/09/2015 7:48	176	29	**0.16**
MD4			
R-Off | AC-Off | Fn-50%	195	39	0.20
8/09/2015 7:58	145	26	**0.18**
8/09/2015 11:34	290	64	0.22
MD2			
R-On | AC-Off | Fn-50%	173	55	0.32
9/09/2015 9:50	173	50	0.29
8/09/2015 10:04	173	58	0.34
MD3			
R-OnOff | AC-Off | Fn-50%	193	46	0.24
8/09/2015 16:54	196	45	0.23
9/09/2015 11:03	187	48	0.26
LCT			
East Bound			
MD1			
R-On | AC-On | Fn-50%	328	54	**0.17**
8/09/2015 14:38	243	54	0.22
9/09/2015 7:10	435	52	**0.12**
9/09/2015 11:56	188	60	0.32
MD4			
R-Off | AC-Off | Fn-50%	341	58	**0.17**
8/09/2015 7:30	341	58	**0.17**
MD2			
R-On | AC-Off | Fn-50%	315	70	0.22
9/09/2015 9:32	273	73	0.27
8/09/2015 9:53	382	66	**0.17**
MD3			
R-OnOff | AC-Off | Fn-50%	249	49	**0.20**
8/09/2015 16:41	230	45	**0.19**
9/09/2015 10:53	296	59	0.20
8/09/2015 12:36	218	42	**0.19**
West Bound			
MD1			
R-On | AC-On | Fn-50%	135	48	0.36
9/09/2015 11:50	170	55	0.33
8/09/2015 9:32	113	38	0.34
8/09/2015 12:22	123	52	0.42
MD4			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
R-Off | AC-Off | Fn-50%	119	37	0.31
8/09/2015 18:27	122	40	0.33
9/09/2015 9:09	116	34	0.30
MD2			
R-On | AC-Off | Fn-50%	127	38	0.30
8/09/2015 16:32	127	38	0.30
MD3			
R-OnOff | AC-Off | Fn-50%	129	44	0.34
9/09/2015 10:46	155	39	0.25
8/09/2015 10:56	102	49	0.48
M5T			
East Bound			
MD1			
R-On | AC-On | Fn-50%	510	194	0.38
9/09/2015 11:28	606	192	0.32
8/09/2015 8:24	406	190	0.47
8/09/2015 11:58	546	202	0.37
MD4			
R-Off | AC-Off | Fn-50%	275	80	0.29
8/09/2015 17:41	245	71	0.29
9/09/2015 8:19	291	85	0.29
MD2			
R-On | AC-Off | Fn-50%	366	134	0.37
8/09/2015 15:37	366	134	0.37
MD3			
R-OnOff | AC-Off | Fn-50%	408	134	0.33
9/09/2015 10:23	360	99	0.28
8/09/2015 10:33	450	165	0.37
West Bound			
MD1			
R-On | AC-On | Fn-50%	299	107	0.36
8/09/2015 15:07	328	131	0.40
9/09/2015 8:00	217	39	**0.18**
MD4			
R-Off | AC-Off | Fn-50%	320	99	0.31
8/09/2015 8:11	290	62	0.22
8/09/2015 11:45	355	142	0.40
MD2			
R-On | AC-Off | Fn-50%	403	99	0.25
9/09/2015 10:03	434	78	**0.18**

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
8/09/2015 10:22	368	122	0.33
MD3			
R-OnOff | AC-Off | Fn-50%	287	86	0.30
8/09/2015 17:20	287	86	0.30
SHT			
North Bound			
MD1			
R-On | AC-On | Fn-50%	184	69	0.38
9/09/2015 11:44	187	67	0.36
8/09/2015 9:24	174	64	0.37
8/09/2015 12:15	197	79	0.40
MD4			
R-Off | AC-Off | Fn-50%	175	55	0.31
8/09/2015 18:17	171	59	0.35
9/09/2015 9:02	182	48	0.26
MD2			
R-On | AC-Off | Fn-50%	172	67	0.39
8/09/2015 16:24	172	67	0.39
MD3			
R-OnOff | AC-Off | Fn-50%	104	55	0.52
9/09/2015 10:40	97	46	0.48
8/09/2015 10:50	114	66	0.58
South Bound			
MD1			
R-On | AC-On | Fn-50%	53	23	0.43
8/09/2015 14:46	52	25	0.48
9/09/2015 7:45	54	19	0.36
MD4			
R-Off | AC-Off | Fn-50%	46	33	**0.71**
8/09/2015 11:31	46	33	**0.71**
MD2			
R-On | AC-Off | Fn-50%	63	40	0.64
9/09/2015 9:46	69	37	0.53
8/09/2015 10:01	56	43	**0.78**
MD3			
R-OnOff | AC-Off | Fn-50%	60	35	0.59
8/09/2015 16:49	74	34	0.46
9/09/2015 11:00	40	37	**0.92**
Car 6 - Subaru			
EDMT			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
North Bound			
MD1			
R-On | AC-On | Fn-50%	106	27	0.26
10/09/2015 13:22	121	21	**0.18**
11/09/2015 13:22	96	31	0.32
MD4			
R-Off | AC-Off | Fn-50%	113	92	**0.82**
10/09/2015 15:14	118	87	**0.73**
11/09/2015 15:10	108	98	**0.91**
South Bound			
MD2			
R-On | AC-Off | Fn-50%	281	52	**0.19**
11/09/2015 14:01	281	52	**0.19**
MD3			
R-OnOff | AC-Off | Fn-50%	141	37	0.26
10/09/2015 12:29	116	26	0.22
10/09/2015 13:49	168	49	0.29
LCT			
East Bound			
MD1			
R-On | AC-On | Fn-50%	268	136	0.51
11/09/2015 15:29	268	136	0.51
MD2			
R-On | AC-Off | Fn-50%	317	48	**0.15**
11/09/2015 13:49	317	48	**0.15**
MD3			
R-OnOff | AC-Off | Fn-50%	243	31	**0.13**
10/09/2015 13:39	265	42	**0.16**
10/09/2015 12:18	221	19	**0.09**
West Bound			
MD1			
R-On | AC-On | Fn-50%	133	28	0.21
10/09/2015 13:32	142	26	**0.18**
11/09/2015 13:31	124	30	0.24
MD4			
R-Off | AC-Off | Fn-50%	166	117	**0.71**
10/09/2015 15:24	180	133	**0.74**
11/09/2015 15:21	152	102	0.67
M5T	405	83	0.21
East Bound			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
MD1			
R-On | AC-On | Fn-50%	484	44	0.09
10/09/2015 12:55	470	53	0.11
11/09/2015 13:08	496	36	0.07
MD4			
R-Off | AC-Off | Fn-50%	421	293	0.70
10/09/2015 14:28	456	331	0.73
11/09/2015 14:34	384	253	0.66
West Bound			
MD2			
R-On | AC-Off | Fn-50%	390	42	0.11
11/09/2015 14:20	390	42	0.11
MD3			
R-OnOff | AC-Off | Fn-50%	372	33	0.09
10/09/2015 12:41	399	25	0.06
10/09/2015 14:05	344	42	0.12
SHT			
North Bound			
MD1			
R-On | AC-On | Fn-50%	186	29	0.16
10/09/2015 13:25	212	27	0.13
11/09/2015 13:25	161	32	0.20
MD4			
R-Off | AC-Off | Fn-50%	166	126	0.76
10/09/2015 15:17	159	120	0.76
11/09/2015 15:13	176	133	0.76
South Bound			
MD2			
R-On | AC-Off | Fn-50%	79	40	0.51
11/09/2015 13:57	79	40	0.51
MD3			
R-OnOff | AC-Off | Fn-50%	85	29	0.34
10/09/2015 13:46	55	34	0.62
10/09/2015 12:26	105	25	0.24
Car 7 - Toyota Corolla			
EDMT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	107	85	0.79
15/09/2015 16:45	103	97	0.94

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
16/09/2015 11:08	115	64	0.56
MD2			
R-On | AC-Off | Fn-50%	135	25	**0.18**
15/09/2015 14:59	122	18	**0.15**
16/09/2015 9:24	146	29	0.20
MD3			
R-OnOff | AC-Off | Fn-50%	81	43	0.53
15/09/2015 19:03	81	43	0.53
South Bound			
MD1			
R-On | AC-On | Fn-50%	159	13	**0.08**
15/09/2015 14:09	159	17	**0.11**
15/09/2015 17:44	171	11	**0.07**
16/09/2015 7:50	140	15	**0.11**
MD3			
R-OnOff | AC-Off | Fn-50%	223	60	0.27
15/09/2015 15:41	210	64	0.30
16/09/2015 10:15	259	48	**0.18**
LCT			
East Bound			
MD1			
R-On | AC-On | Fn-50%	233	16	**0.07**
15/09/2015 13:58	212	13	**0.06**
15/09/2015 17:23	226	16	**0.07**
16/09/2015 7:25	253	19	**0.07**
MD4			
R-Off | AC-Off | Fn-50%	417	197	0.47
16/09/2015 12:15	417	197	0.47
MD3			
R-OnOff | AC-Off | Fn-50%	343	44	**0.13**
15/09/2015 15:28	258	53	0.21
16/09/2015 10:04	411	36	**0.09**
West Bound			
MD1			
R-On | AC-On | Fn-50%	78	12	**0.16**
16/09/2015 7:15	78	12	**0.16**
MD4			
R-Off | AC-Off | Fn-50%	160	103	0.65
15/09/2015 16:59	159	117	**0.74**
16/09/2015 12:05	162	89	0.55

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
MD2			
R-On | AC-Off | Fn-50%	143	20	**0.14**
15/09/2015 15:08	157	20	**0.12**
16/09/2015 9:34	130	19	**0.15**
M5T			
East Bound			
MD4			
R-Off | AC-Off | Fn-50%	398	236	0.59
15/09/2015 16:32	368	283	**0.77**
16/09/2015 10:54	420	201	0.48
MD2			
R-On | AC-Off | Fn-50%	425	28	**0.06**
15/09/2015 14:45	438	36	**0.08**
16/09/2015 8:37	415	21	**0.05**
MD3			
R-OnOff | AC-Off | Fn-50%	338	38	**0.11**
15/09/2015 18:38	338	38	**0.11**
West Bound			
MD1			
R-On | AC-On | Fn-50%	384	20	**0.05**
15/09/2015 14:24	546	24	**0.04**
15/09/2015 18:23	229	14	**0.06**
16/09/2015 8:06	377	22	**0.06**
MD3			
R-OnOff | AC-Off | Fn-50%	414	49	**0.12**
15/09/2015 16:16	460	47	**0.10**
16/09/2015 10:29	308	54	**0.18**
SHT			
North Bound			
MD4			
R-Off | AC-Off | Fn-50%	204	140	0.69
15/09/2015 16:51	219	182	**0.83**
16/09/2015 11:11	181	79	0.44
MD2			
R-On | AC-Off | Fn-50%	168	21	**0.13**
15/09/2015 15:01	168	19	**0.12**
16/09/2015 9:27	169	24	**0.14**
MD3			
R-OnOff | AC-Off | Fn-50%	87	41	0.47
15/09/2015 19:05	87	41	0.47

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
South Bound			
MD1			
R-On | AC-On | Fn-50%	91	14	**0.16**
15/09/2015 14:05	51	22	0.43
15/09/2015 17:32	112	13	**0.11**
16/09/2015 7:45	67	13	**0.19**
MD3			
R-OnOff | AC-Off | Fn-50%	76	46	0.60
15/09/2015 15:35	69	46	0.67
16/09/2015 10:12	85	45	0.53
Car 8 - Fiat Punto			
EDMT			
North Bound			
MD1			
R-On | AC-On | Fn-50%	143	19	**0.13**
17/09/2015 18:49	143	19	**0.13**
MD4			
R-Off | AC-Off | Fn-50%	108	96	**0.89**
16/09/2015 18:20	109	93	**0.85**
17/09/2015 10:56	120	112	**0.93**
17/09/2015 17:36	93	82	**0.88**
MD2			
R-On | AC-Off | Fn-50%	124	24	**0.20**
16/09/2015 16:27	104	25	0.24
17/09/2015 8:43	137	19	**0.14**
17/09/2015 14:53	126	29	0.23
South Bound			
MD1			
R-On | AC-On | Fn-50%	163	27	**0.16**
16/09/2015 15:02	157	28	**0.18**
17/09/2015 7:07	219	26	**0.12**
17/09/2015 13:46	127	37	0.29
17/09/2015 18:34	121	21	**0.17**
MD3			
R-OnOff | AC-Off | Fn-50%	148	46	0.31
16/09/2015 17:11	177	52	0.29
17/09/2015 9:30	129	41	0.32
17/09/2015 15:28	131	44	0.33
LCT			
East Bound			

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
MD1			
R-On | AC-On | Fn-50%	268	34	**0.13**
16/09/2015 14:51	221	25	**0.11**
17/09/2015 6:50	387	31	**0.08**
17/09/2015 13:35	260	27	**0.10**
17/09/2015 17:54	203	45	0.22
MD3			
R-OnOff | AC-Off | Fn-50%	276	43	**0.15**
16/09/2015 16:48	295	40	**0.13**
17/09/2015 9:19	290	46	**0.16**
17/09/2015 15:12	243	42	**0.17**
West Bound			
MD4			
R-Off | AC-Off | Fn-50%	120	86	**0.72**
16/09/2015 18:30	92	78	**0.85**
17/09/2015 11:05	127	87	0.68
17/09/2015 17:47	142	94	0.67
MD2			
R-On | AC-Off | Fn-50%	144	30	0.21
16/09/2015 16:38	189	33	**0.17**
17/09/2015 8:54	112	24	0.21
17/09/2015 15:04	124	33	0.26
M5T			
East Bound			
MD4			
R-Off | AC-Off | Fn-50%	384	281	**0.73**
16/09/2015 18:05	281	212	**0.75**
17/09/2015 10:41	523	374	**0.71**
17/09/2015 16:35	330	245	**0.74**
MD2			
R-On | AC-Off | Fn-50%	374	33	**0.09**
16/09/2015 15:45	345	34	**0.10**
17/09/2015 8:10	379	25	**0.07**
17/09/2015 14:25	396	45	**0.11**
West Bound			
MD1			
R-On | AC-On | Fn-50%	468	44	**0.09**
16/09/2015 15:27	499	42	**0.08**
17/09/2015 7:21	268	50	**0.19**
17/09/2015 14:04	495	44	**0.09**

Setting / Time of entry into tunnel	Average external NO_2 concentration (ppb)	Average internal NO_2 concentration (ppb)	Average I/O ratio (paired)
MD3			
R-OnOff | AC-Off | Fn-50%	293	38	0.13
16/09/2015 17:17	91	67	0.73
16/09/2015 17:46	215	33	0.16
17/09/2015 9:48	431	35	0.08
17/09/2015 16:19	300	42	0.14
SHT			
North Bound			
MD1			
R-On | AC-On | Fn-50%	153	35	0.23
17/09/2015 18:53	153	35	0.23
MD4			
R-Off | AC-Off | Fn-50%	146	114	0.78
16/09/2015 18:23	133	103	0.77
17/09/2015 10:59	158	120	0.76
17/09/2015 17:40	148	118	0.80
MD2			
R-On | AC-Off | Fn-50%	195	27	0.14
16/09/2015 16:31	214	27	0.12
17/09/2015 8:47	158	21	0.13
17/09/2015 14:56	211	35	0.16
South Bound			
MD1			
R-On | AC-On | Fn-50%	88	25	0.29
16/09/2015 14:59	54	36	0.65
17/09/2015 7:01	56	35	0.63
17/09/2015 13:42	18	42	2.36
17/09/2015 18:20	108	19	0.18
MD3			
R-OnOff | AC-Off | Fn-50%	112	30	0.27
16/09/2015 17:01	121	24	0.20
17/09/2015 9:27	49	35	0.72
17/09/2015 15:20	124	36	0.29

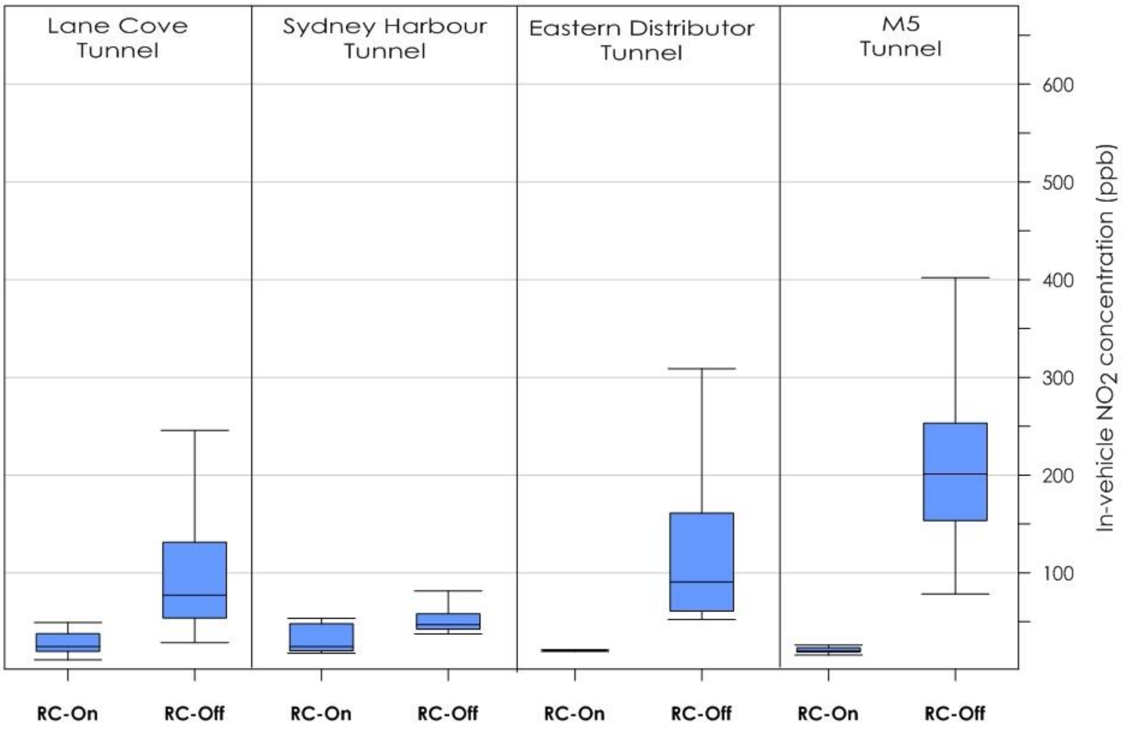
Average I/O ratio references:

Green = Values less than 0.2
Black = Values between 0.2 and 0.7
Red = Values greater than 0.7

Appendix E BOX PLOTS

IN-VEHICLE NO_2 CONCETRATION

Comparison of In- Vehicle NO_2 concentration for four major tunnels



RC-On = Air Recirculation On, Air conditioning Off, Fan speed 50%

RC-Off = Air Recirculation Off, Air conditioning Off, Fan speed 50%

Figure E-1: In-Vehicle NO_2 concentration 2008 Holden Astra Wagon – Prescribed Direction

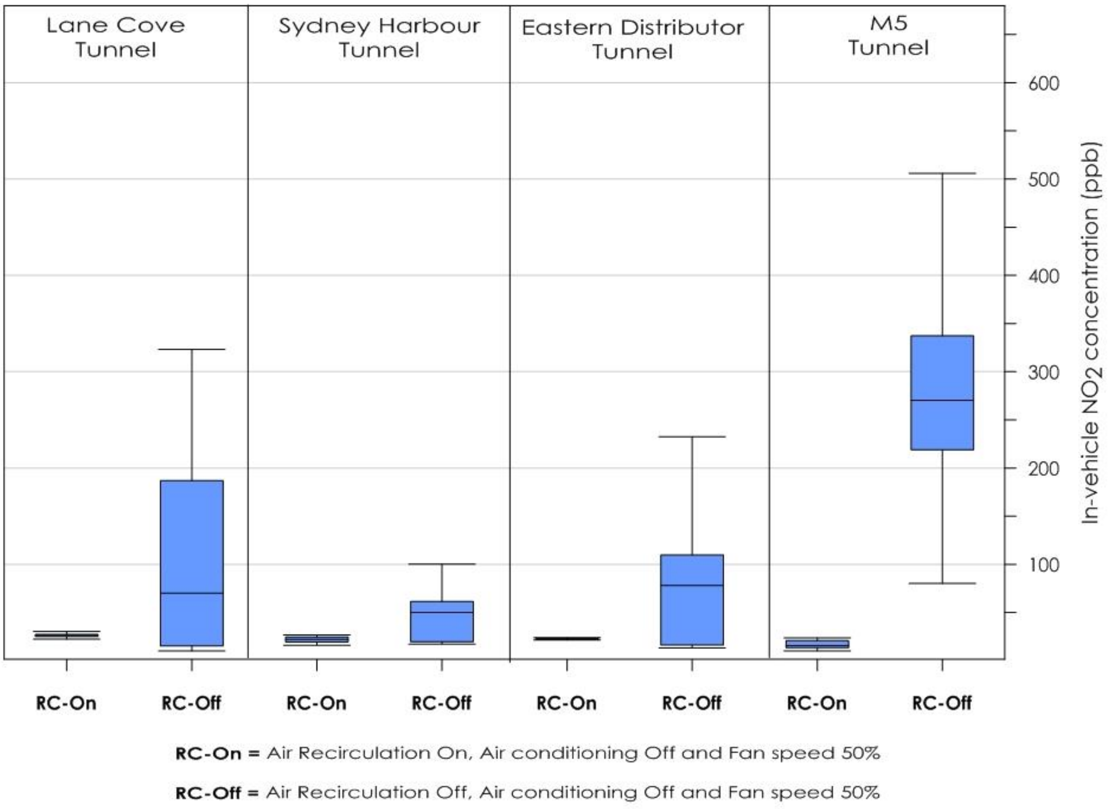


Figure E-2: In-Vehicle NO_2 concentration 2014 Hyundai i30 – Prescribed Direction

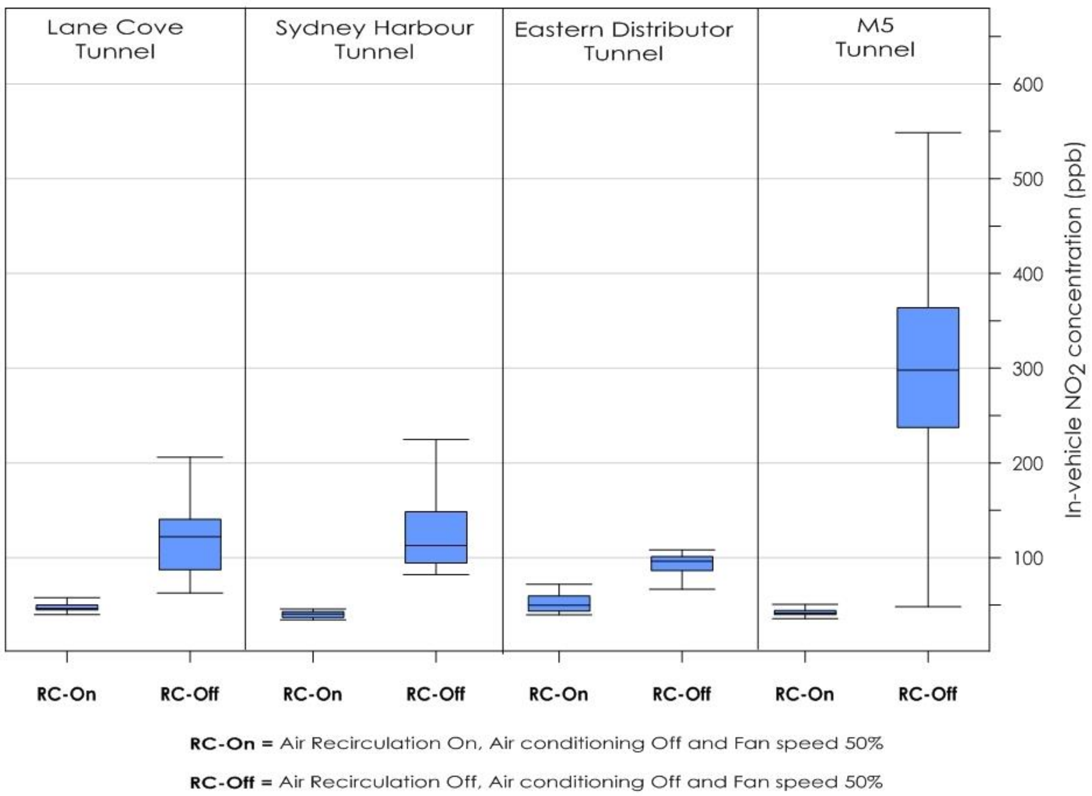


Figure E-3: In-Vehicle NO_2 concentration 2001 Subaru Outback – Counter Direction

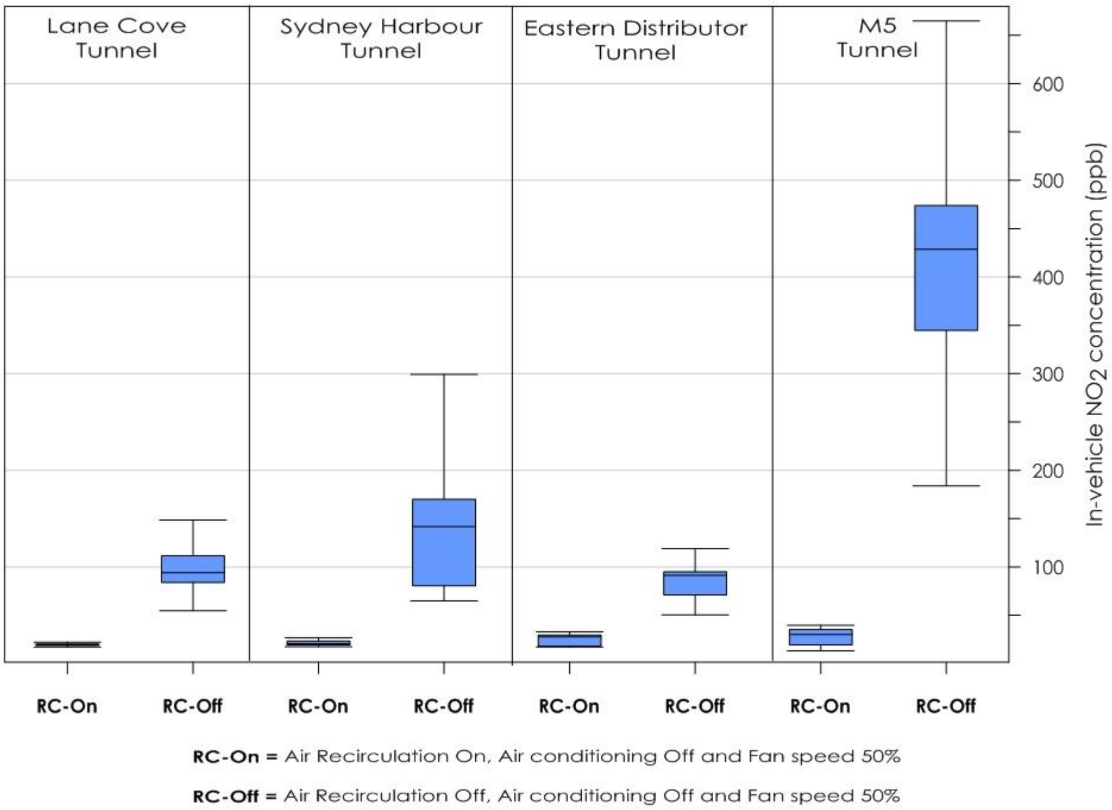


Figure E-4: In-Vehicle NO_2 concentration 2011 Toyota Corolla – Counter Direction

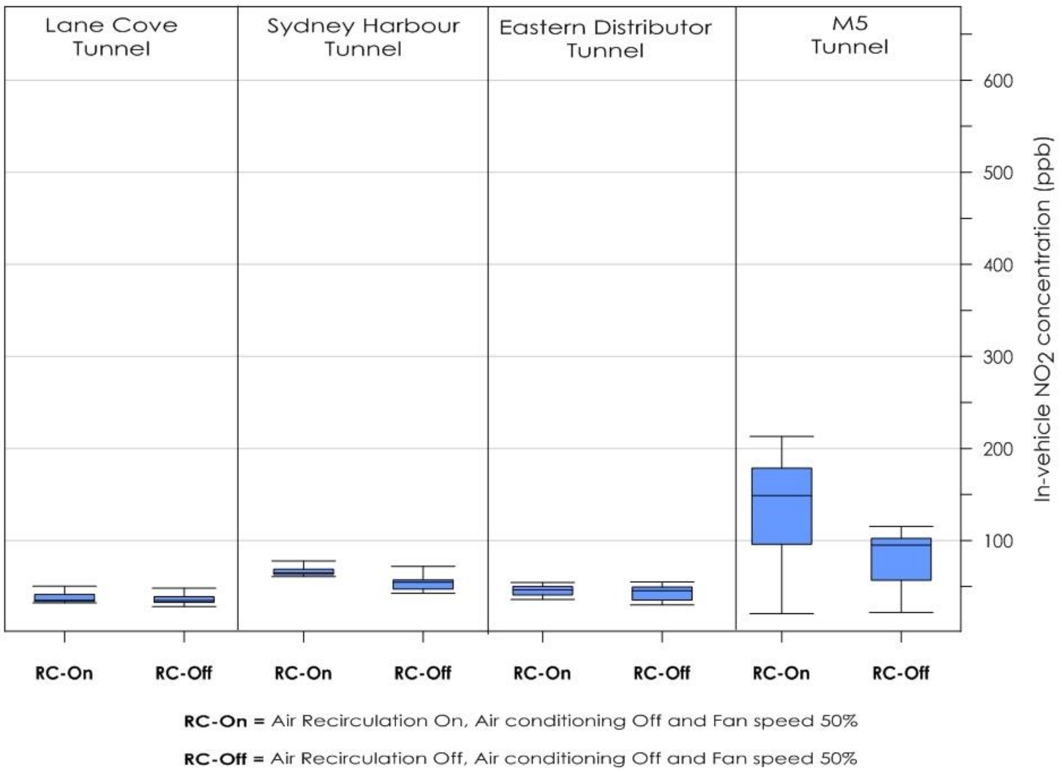


Figure E-5: In-Vehicle NO_2 concentration 2002 Audi A3 – Counter Direction

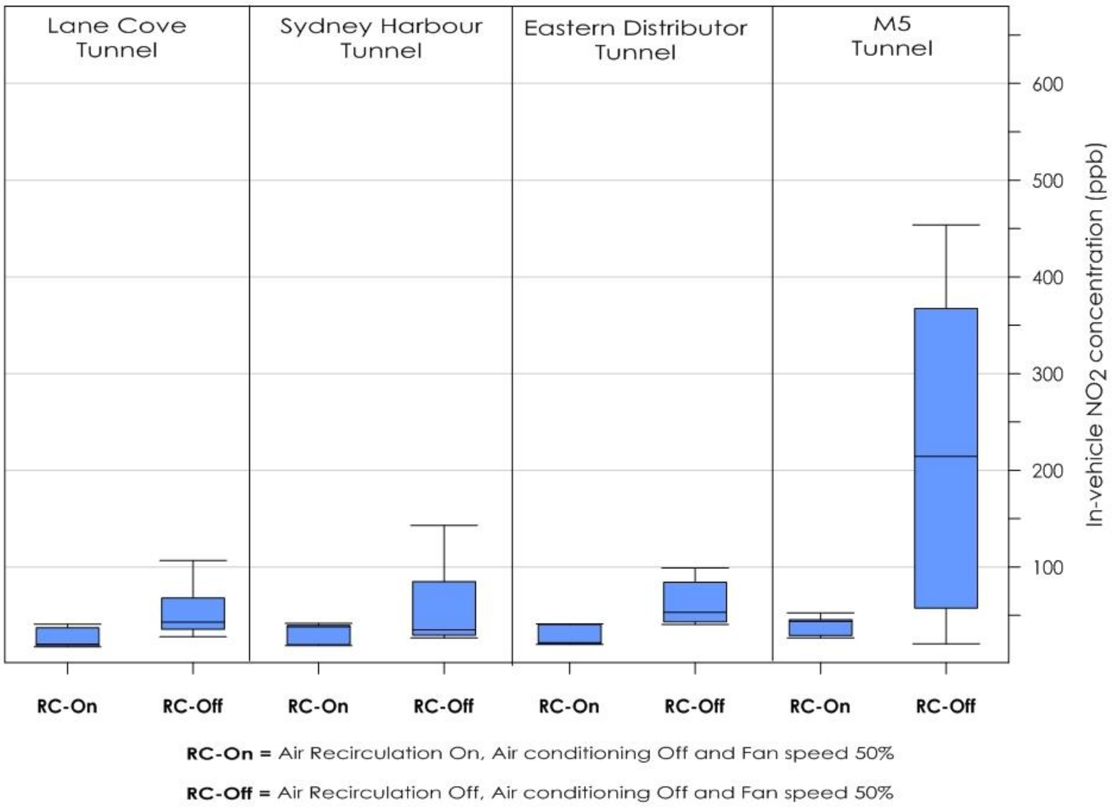


Figure E-6: In-Vehicle NO_2 concentration 2014 BMW Prestige – Counter Direction

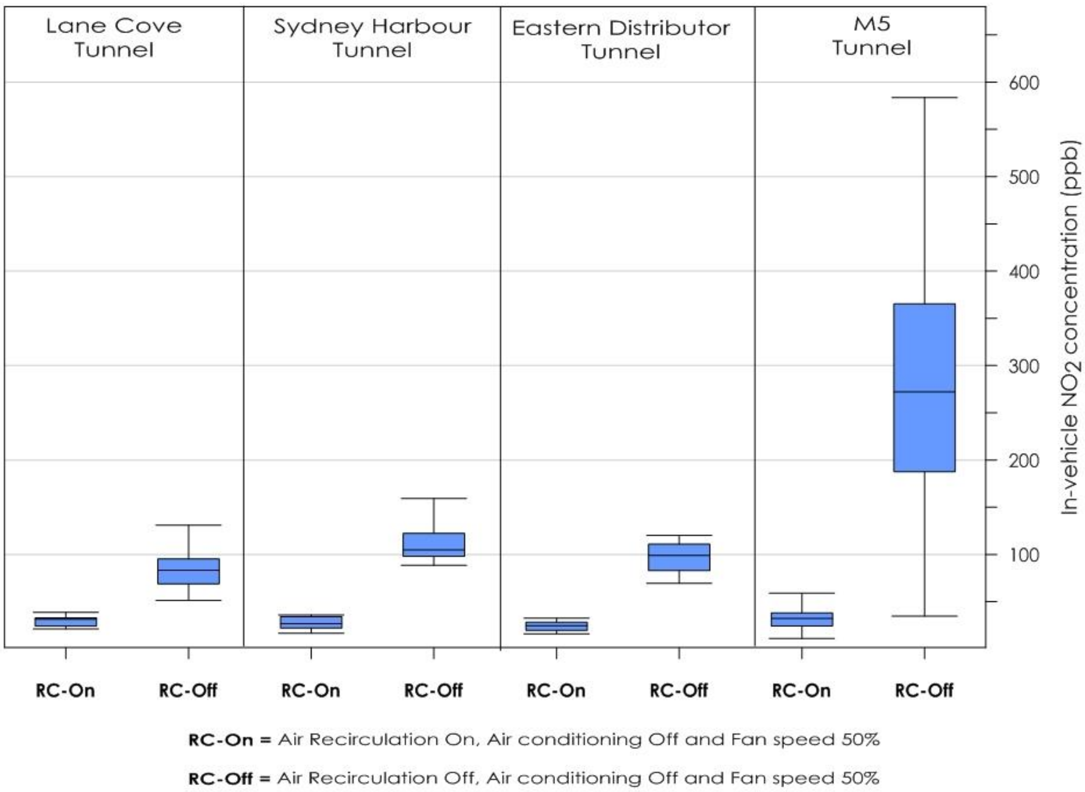


Figure E-7: In-Vehicle NO_2 concentration 2007 Fiat Punto – Counter Direction

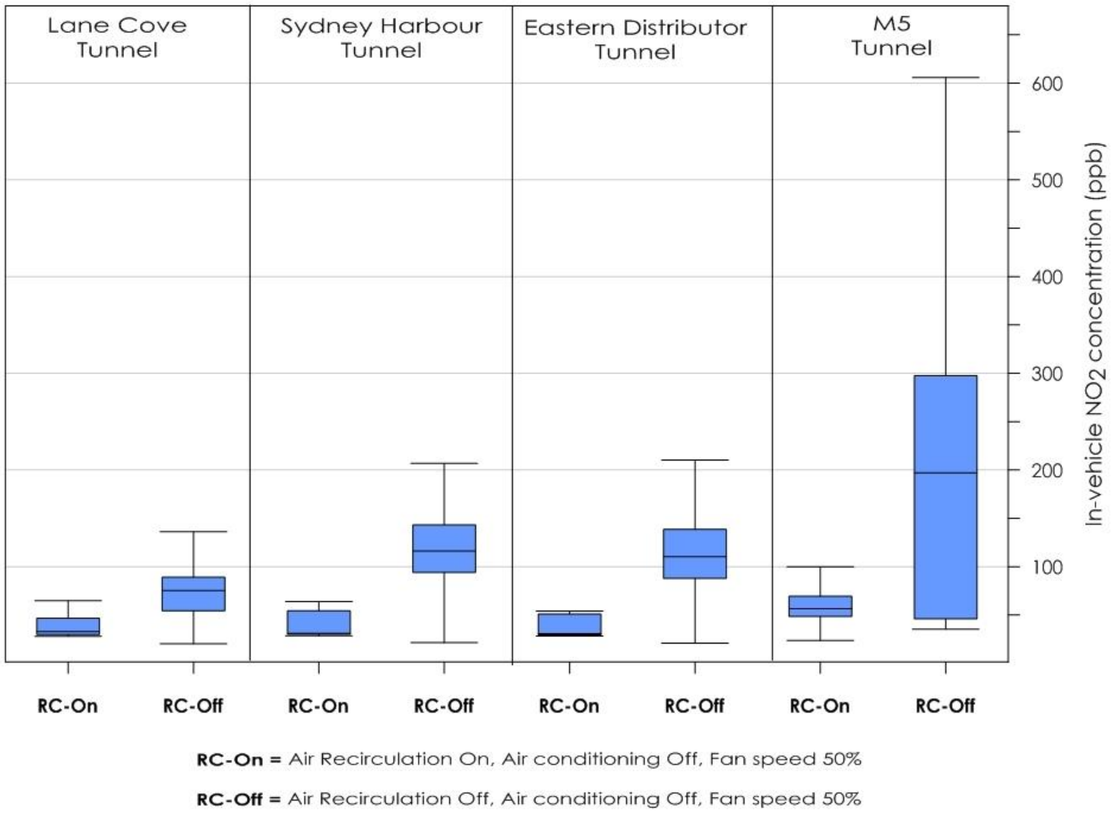


Figure E-8: In-Vehicle NO_2 concentration 2002 Ford Fiesta – Counter Direction