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# In-vehicle nitrogen dioxide concentrations in road tunnels

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## HIGHLIGHTS

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

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## ABSTRACT

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


## 1. Introduction

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

Exposure to $NO_2$ is associated with direct, adverse effects on health, even after adjustment for the effects of other pollutants (WHO Regional Office for Europe, 2013; US EPA, 2015), and $NO_2$ is considered to be a more important pollutant than NO from a health perspective. The main health effects of short-term $NO_2$ exposure

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(<30 min) at concentrations that are representative of road tunnels (<500 ppb) include increased airway responsiveness, decreased lung function, and an increase in blood inflammation markers (Jalaludin, 2015); however, no health effects were identified effects at $NO_2$ concentrations <200 ppb. Since vehicle emissions are a major source of $NO_2$, vehicle occupants in urban environments are expected to be at the greatest risk to these effects (Dons et al., 2012). Despite this, measurements of $NO_2$ concentrations in vehicle cabins (herein referred to as 'in-vehicle') are limited as previous studies typically have measured other pollutants, such as carbon monoxide (e.g. Colwill and Hickman, 1980; Clifford et al., 1997; Chan et al., 2002), and particulate matter (e.g. Knibbs et al., 2010; Hudda et al., 2012; Goel and Kumar 2015).

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

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

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

## 2. Experimental work

### 2.1. Overview

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

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

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

### 2.2. Monitoring equipment and procedures

#### 2.2.1. Carbon dioxide

Previous studies have shown that in-vehicle $CO_2$ levels typically reach around 2000–3000 parts per million (ppm) with an outside-vehicle concentration of around 400 ppm (e.g. Fruin et al., 2011). Highly sensitive laboratory-grade instruments are generally not required for AER studies, and $CO_2$ can be successfully measured using portable instruments. The instrument used to measure $CO_2$ in the study was the LI-COR Li-820, which employed a non-dispersive infrared detection technique. The Li-820 was pump driven, thus allowing a fast response time. It had a 1 ppm signal noise at 370 ppm $CO_2$, and a range of 0–20,000 ppm.

#### 2.2.2. Nitrogen dioxide

A transit through a 4-km long road tunnel at a speed of 80 km/h (optimal traffic flow) only takes 3 min. Sub-minute averaging periods and a fast instrument response were therefore required to give an adequate temporal resolution in the $NO_2$ measurements. The instrument resolution also needed to enable a clear differentiation between in-vehicle and in-tunnel concentrations. $NO_2$ was measured using two cavity attenuated phase shift (CAPS) analysers (Aerodyne) (Kebabian et al., 2008). The CAPS analyser was chosen for its ability to measure $NO_2$ with a high temporal resolution (frequency of 1 Hz), a high precision (resolution of 1 ppb), and