IMPLICATIONS OF THE EVOLVING VEHICLE FLEET ON VENTILATION ENERGY CONSUMPTION IN NSW ROAD TUNNELS

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Abstract

The purpose of this paper was to investigate the implications of the evolving vehicle fleet on ventilation energy consumption in New South Wales (NSW) road tunnels. Three forecasts of the NSW vehicle fleet were developed, incorporating the adoption of alternative fuel vehicles. The NSW emissions estimation model and PIARC (2019) utilised the three forecasts to estimate vehicle emissions in future years up to 2040. This model was validated for the year 2018 in a Sydney urban road tunnel. As the NSW vehicle fleet evolves and vehicle technology improves, ventilation fresh air requirements for the dilution of emissions were modelled to reduce over time. The project measured the impact of changes to air quality criteria by relaxing the zero net portal emissions to allow portal discharge at an acceptable NO_2 exit-portal concentration of 0.12ppm. Annual energy savings were quantified for a hypothetical road tunnel. Analysis for the expected case fleet forecast concluded potential savings in annual energy consumption, financial costs and greenhouse gas emissions of ~83% when compared to the status quo.

Keywords: road tunnel ventilation, energy consumption, vehicle fleet, emissions estimation

1 Introduction

Road tunnels seek to improve the efficiency, safety and reliability of all road user journeys by reducing congestion on arterial and local surface roads, providing a higher level of traffic flow service and connecting key strategic commuter and freight routes across a road network. Mechanical ventilation systems are designed to dilute vehicle emissions to meet in-tunnel air quality requirements, prevent tunnel air from escaping through tunnel portals and to maintain a critical velocity in fire scenarios to prevent back-layering of smoke. Ventilation systems in New South Wales (NSW) road tunnels currently consume high levels of energy to operate axial fans and jet fans. The financial and environmental costs associated with the operation of road tunnel ventilation systems are significant.

One of the key changes that will affect the operation of future road tunnel ventilation systems is the evolving NSW vehicle fleet. Over the next 40 years, it is anticipated that vehicle propulsion systems in the NSW fleet will transition from traditional Internal Combustion Engine (ICE) vehicles (petrol and diesel) to hybrid, electric and alternative fuel vehicles (AFVs). AFVs are defined as natural gas, hydrogen, electric and hybrid vehicles.

A transformation of the NSW fleet (with the adoption and growth of AFVs) would result in a proportional reduction in vehicle emissions. Lower levels of mechanical ventilation would be required to achieve the air demand to dilute vehicle emissions to meet current air quality criteria. In the future, the air quality within road tunnels may trend towards equivalence to the air quality outside the tunnel.

Even though vehicle emissions may trend downwards, reductions in required mechanical ventilation levels would not be realised under the current road tunnel design criteria. The dominating requirement for future ventilation systems is the adherence to "only release emissions from ventilation outlets and not from the portals" under the Minister's Conditions of Approval (COA) for each road tunnel project (Department of Planning and Environment, 2019). This requirement is also referred to as the "zero net portal emissions" requirement. An illustration of tunnel air flows to avoid portal emissions is presented in Figure 1.

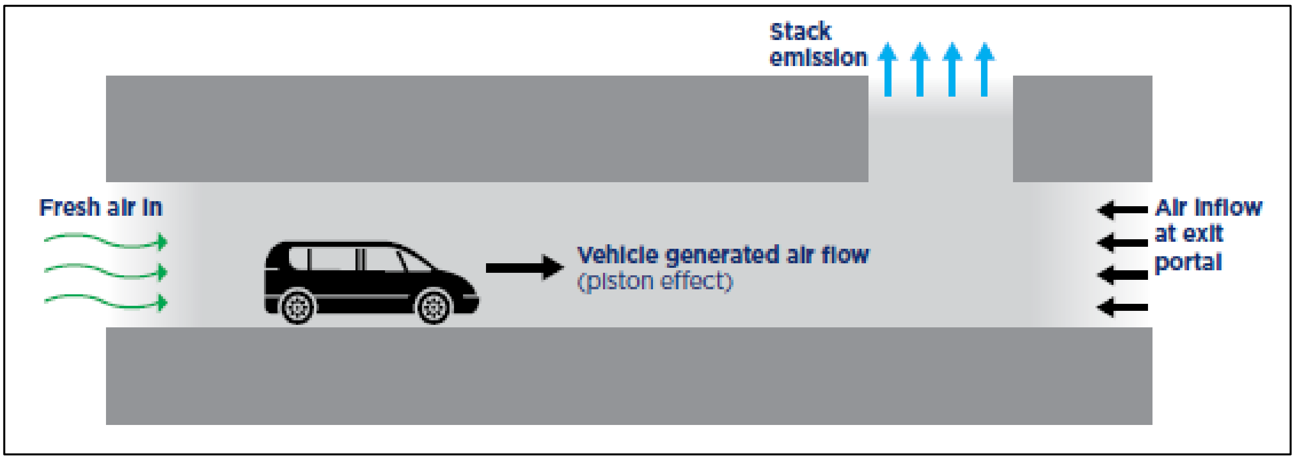


Figure 1 Illustration of tunnel air flow direction to avoid portal emissions (ACTAQ, 2014)

Hypothetically, if the NSW vehicle fleet transitions to 100% AFVs in the future and the "zero net portal emissions" criterion is still in place, it is currently anticipated that the ventilation system would be operated to maintain an ingress of air from all tunnel portals to ensure air is exhausted from the ventilation outlet.

1.1 Purpose and Scope

This paper seeks to analyse the combined influence of changing factors and design inputs on future ventilation operation. Specifically, the study aims to synthesise the knowledge of the NSW fleet, growth of AFVs, air quality criteria, tunnel environment heat transfer and ventilation operation mechanisms into a tangible impact. These have been distilled into five questions that support the main purpose of the paper:

1. What are the future trends in the NSW vehicle fleet in terms of composition and magnitude?
2. Does the current RMS NSW emissions estimation model correlate with real-world tunnel data?
3. What are the impacts of changes in the NSW fleet on tunnel ventilation energy consumption?
4. What impacts will variations in air quality criteria have on tunnel ventilation energy consumption?
5. What are the cumulative impacts of the evolving fleet and air quality criteria changes on tunnel ventilation energy consumption?

A conscious decision has been made to take a "ground-up" approach for this study; conducting theoretical analysis rather than employing numerical methods and simulations. The intention is that the conclusions reached at the end of this study are derived from the analysis of commonly available data, the use of theoretical concepts and methods that clearly state the assumptions and allow for further scrutiny in future research.

2 Background

2.1 Vehicle Emissions and Air Demand for Ventilation

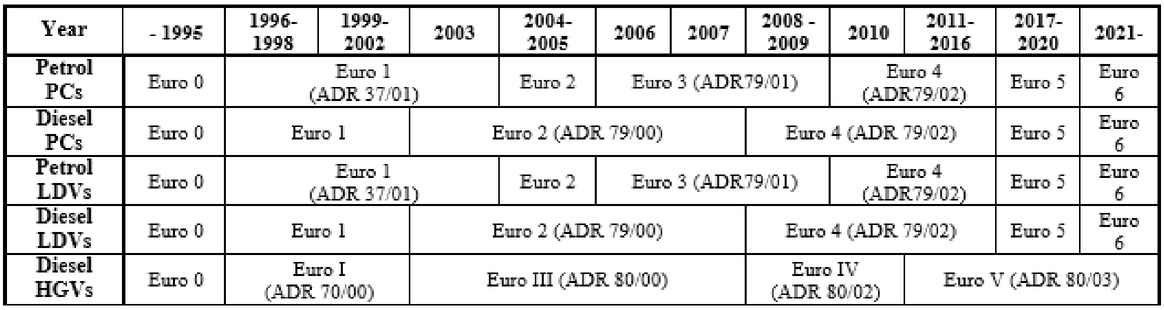
In 2019, PIARC published the latest version of the report Road Tunnels: Vehicle Emissions and Air Demand for Ventilation. This report is the industry's leading reference and guidance document in the design of road tunnel ventilation systems. The report sets out the methodology to calculate the minimum air demand required to dilute vehicle emissions (CO, NO_x and PM) to achieve the air quality criteria.

PIARC (2019) presents two methodologies for calculating air demand: the standard method and the fleet-specific method. The standard method involves utilising generic emissions tables based on the 2018 European vehicle fleet. This method is not applicable to NSW as the average year model of the Australian vehicle fleet lags the European vehicle fleet by approximately 4-7 years.

The fleet-specific method involves utilising the NSW fleet composition presented in O'Kelly, Casey & Garland (2016) in combination with base emissions factors provided in the appendix of PIARC (2019). Emissions factors are presented for each European Vehicle (EURO) standard. EURO standards are legislated European Union directives that specify the maximum levels of different emissions for vehicles manufactured in a certain year. In Australia these standards are termed Australian Design Rules (ADR). The periods of implementation for vehicle emissions standards in Australian with the equivalent EURO standard are depicted in Table 1.

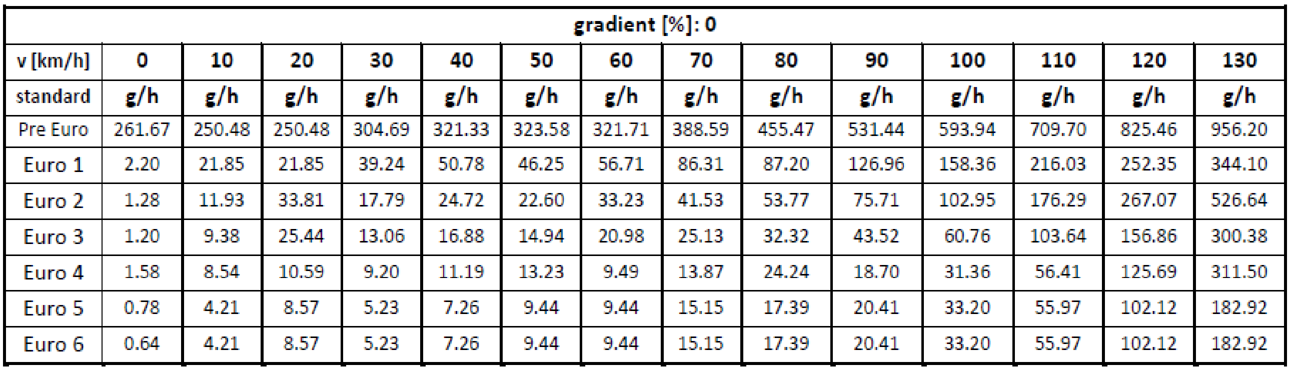
The emissions factor tables specify the rate of emissions (grams per hour) for each pollutant, speed, gradient and EURO standard, exemplified in Table 2.

Table 1 Periods of implementation for vehicle emissions standards in Australia (O'Kelly, Casey, & Garland, 2016)



Year	- 1995	1996-1998	1999-2002	2003	2004-2005	2006	2007	2008 - 2009	2010	2011-2016	2017-2020	2021-
Petrol PCs	Euro 0	Euro 1 (ADR 37/01)			Euro 2	Euro 3 (ADR79/01)			Euro 4 (ADR79/02)		Euro 5	Euro 6
Diesel PCs	Euro 0	Euro 1		Euro 2 (ADR 79/00)				Euro 4 (ADR 79/02)			Euro 5	Euro 6
Petrol LDVs	Euro 0	Euro 1 (ADR 37/01)			Euro 2	Euro 3 (ADR79/01)			Euro 4 (ADR79/02)		Euro 5	Euro 6
Diesel LDVs	Euro 0	Euro 1		Euro 2 (ADR 79/00)				Euro 4 (ADR 79/02)			Euro 5	Euro 6
Diesel HGVs	Euro 0	Euro I (ADR 70/00)		Euro III (ADR 80/00)				Euro IV (ADR 80/02)		Euro V (ADR 80/03)		

Table 2 Passenger Car CO Emissions Factors, Gradient 0% (PIARC, 2019)



gradient [%]: 0														
v [km/h]	0	10	20	30	40	50	60	70	80	90	100	110	120	130
standard	g/h	g/h	g/h	g/h	g/h	g/h	g/h	g/h	g/h	g/h	g/h	g/h	g/h	g/h
Pre Euro	261.67	250.48	250.48	304.69	321.33	323.58	321.71	388.59	455.47	531.44	593.94	709.70	825.46	956.20
Euro 1	2.20	21.85	21.85	39.24	50.78	46.25	56.71	86.31	87.20	126.96	158.36	216.03	252.35	344.10
Euro 2	1.28	11.93	33.81	17.79	24.72	22.60	33.23	41.53	53.77	75.71	102.95	176.29	267.07	526.64
Euro 3	1.20	9.38	25.44	13.06	16.88	14.94	20.98	25.13	32.32	43.52	60.76	103.64	156.86	300.38
Euro 4	1.58	8.54	10.59	9.20	11.19	13.23	9.49	13.87	24.24	18.70	31.36	56.41	125.69	311.50
Euro 5	0.78	4.21	8.57	5.23	7.26	9.44	9.44	15.15	17.39	20.41	33.20	55.97	102.12	182.92
Euro 6	0.64	4.21	8.57	5.23	7.26	9.44	9.44	15.15	17.39	20.41	33.20	55.97	102.12	182.92

The use of the PIARC (2019) emissions rates in combination with the NSW fleet composition is referred to as the RMS NSW emissions estimation model.

2.2 NSW Vehicle Fleet Forecast

The NSW vehicle fleet forecast provides a transparent model of the NSW fleet evolution and the report by O’Kelly, Casey & Garland (2016) is publicly available online. The forecast was based on publicly available RMS vehicle registration statistics up to and including 2015. This enabled vehicle growth and attrition rates to be determined as well as the composition of the fleet in terms of age and fuel type. Results from the report were depicted as fleet profile graphs for the years 2000 to 2040 as shown in Figure 2, an example for passenger cars. The fleet forecast provides the percentage of each EURO emission standard for both petrol and diesel vehicles for each vehicle category: Passenger Cars (PC), Light Duty Vehicles (LDV) and Heavy Goods Vehicles (HGV). These vehicle categories align with PIARC’s (2019) emissions factors and enable the calculation of generated emissions for different tunnel segments.

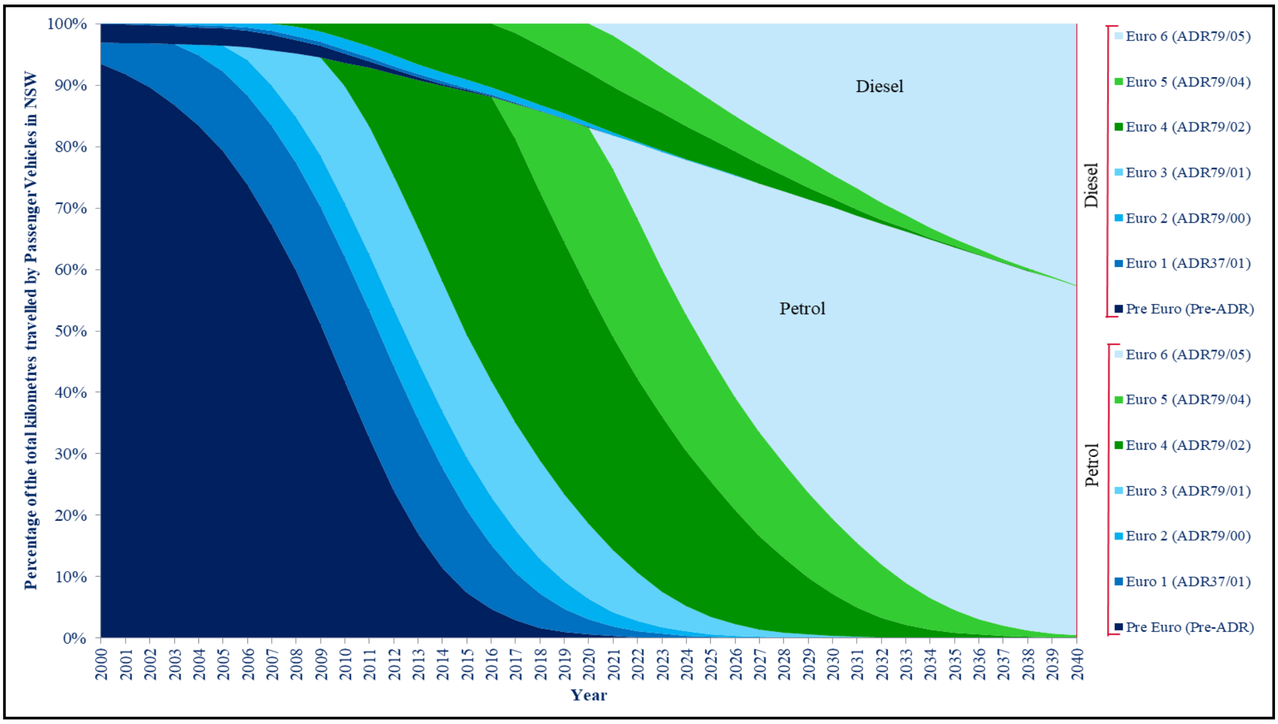


Figure 2 Percentage of kilometres travelled by Passenger Cars in NSW, by EURO standard (O'Kelly, Casey, & Garland, 2016)

2.2.1 Alternative Fuel Vehicles

The NSW fleet forecast only forecasts petrol and diesel vehicles, initially excluding AFVs due to their small proportion of the fleet (<1% in 2018). There are two prominent forecasts for the growth and change in fleet composition of AFVs. The Electric Vehicle (EV) Outlook (Bloomberg New Energy Finance, 2018) forecasts global EV adoption to 2040. Energeia (2018) was commissioned by the Australian Government to assess the Australian EV Market. The NSW government recently released a NSW Electric and Hybrid vehicle plan (Future Transport 2056, 2019) which presents the two models previously mentioned for the NSW and Australian markets respectively. These forecasts are displayed in Figure 3, with cost and price parity points.

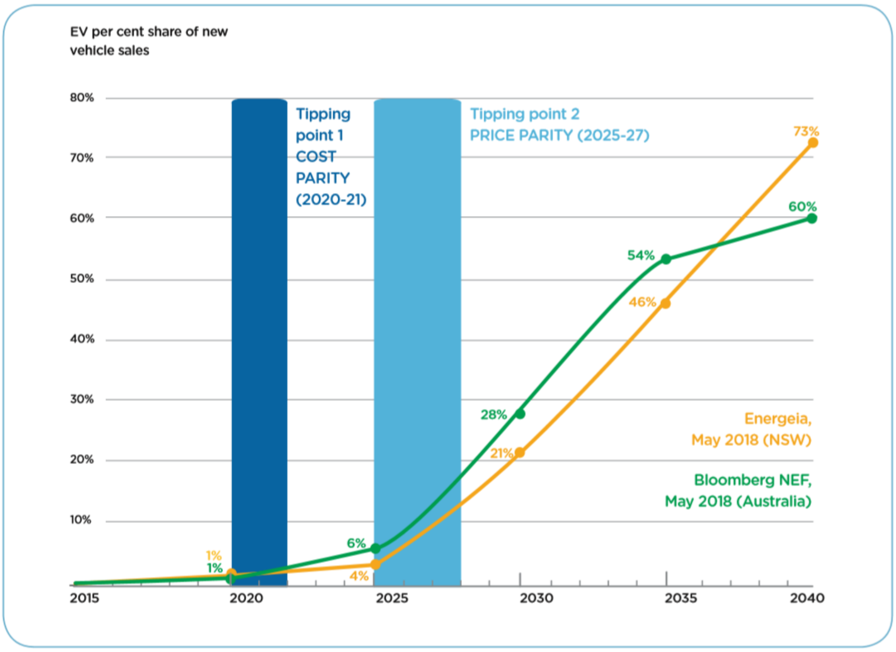


Figure 3 Projected growth of Australian EV market (Future Transport 2056, 2019)

2.3 Air Quality Criteria for NSW Road Tunnels

In-tunnel and ambient air quality criteria are key design requirements for road tunnels in NSW. The purpose of road tunnel ventilation systems is to maintain a safe environment for tunnel occupants and minimise the degradation of air quality for local receptors. Each major NSW road tunnel project has been designed based on the requirements of preceding road tunnels, changing the criteria to reflect community concerns, lessons learnt and updates in research. A comparison of air quality criteria for Sydney's major road tunnels is presented in Table 3. In recent years, NO_2 emissions have become the 'dominant' criterion for which the greatest air demand for dilution is required. The in-tunnel policy states that all new road tunnels greater than 1 kilometre shall be designed to an NO_2 concentration of 0.5ppm on a 15-minute rolling average (ACTAQ, 2016).

Table 3 Air Quality Criteria for NSW major road tunnels (RMS, 2018b; Department of Planning and Environment, 2018)

Tunnel	Year Opened	In-tunnel CO Criterion	In-tunnel NO_2 Criterion	Visibility Criterion	Zero-Portal Emissions Criterion	Ventilation System Configuration
Sydney Harbour Tunnel (SHT)	1992	150 ppm (congested) 125ppm (normal)	-	$0.009m^{-1}$ (congested traffic) $0.005m^{-1}$ (normal traffic)	-	Semi-transverse (operated as longitudinal system)
Eastern Distributor (ED)	2000	87 ppm (15-min avg.) 100 ppm (5-min avg.)	1ppm goal (not a project requirement)	$0.009m^{-1}$ (stopped traffic) $0.005m^{-1}$ (speeds > 50km/h)	-	Longitudinal
M5 East Tunnel (M5E)	2001	87 ppm (15-min avg.)	-	$0.007m^{-1}$ (congested traffic) $0.005m^{-1}$ (free-flowing traffic)	Zero Net Portal Emissions	Longitudinal, with one intermediate exhaust outlet and cross-over fans
Cross City Tunnel (CCT)	2006	87 ppm (15-min avg.) 50 ppm (30-min avg.)	-	$0.007m^{-1}$ (0-20km/h) $0.005m^{-1}$ (free-flowing traffic)	Zero Net Portal Emissions	Longitudinal
Lane Cove Tunnel (LCT)	2007	87 ppm (15-min avg.) 50 ppm (30-min avg.)	-	$0.007m^{-1}$ (0-20km/h) $0.005m^{-1}$ (free-flowing traffic)	Zero Net Portal Emissions	Longitudinal
WestConnex M4 East Tunnel (M4E)	2019	87 ppm (15-min avg.) 50 ppm (30-min avg.)	0.5ppm (15 min avg. in-tunnel)	$0.005m^{-1}$ (15 min. avg.)	Zero Net Portal Emissions	Longitudinal

3 Research Methodology

In seeking to answer the five research questions posed for this study, a model was defined to test the impacts of changes to the NSW fleet forecast and air quality criteria. The methodology followed in this study was:

- Define the project model and associated parameters
- Assess future trends in the NSW Fleet incorporating AFVs
- Validate the current RMS NSW emissions estimation model
- Assess the impacts of NSW fleet trends on ventilation energy consumption
- Assess the impacts of changes to air quality criteria on ventilation energy consumption
- Assess the cumulative impact of changes on ventilation energy consumption

3.1 Project Model Definition

3.1.1 Energy Tunnel Energy Consumption

An analysis of energy consumption data from a Sydney urban road tunnel was undertaken using control system logs from the month of June 2016. The following power ratings and fan efficiencies were provided for equipment in the tunnel:

- Jet Fans: 45 kW (100% efficiency)
- Supply Axial Fans: 376 kW (87% efficiency)
- Cross-Over Axial Fans: 363 kW (Variable efficiency – Data provided in OMCS logs)
- Exhaust Axial Fans: 500 kW (77% efficiency)

The key result was that the ventilation system accounted for **86.3%** of the total energy consumed by the tunnel in the month of June 2016. A breakdown of each subsystem's contribution is provided in Figure 4.

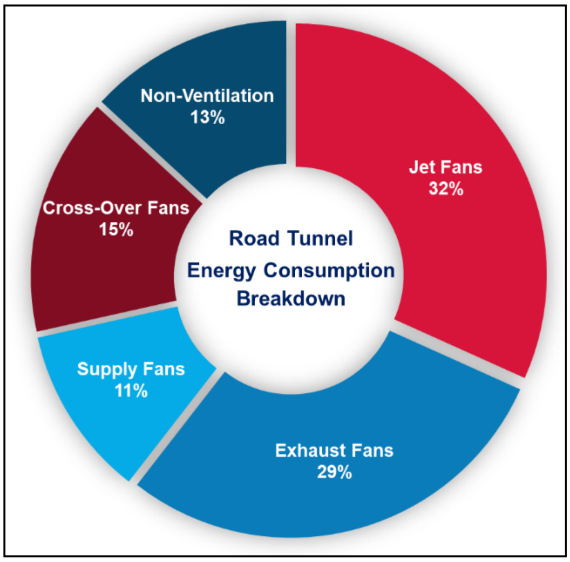
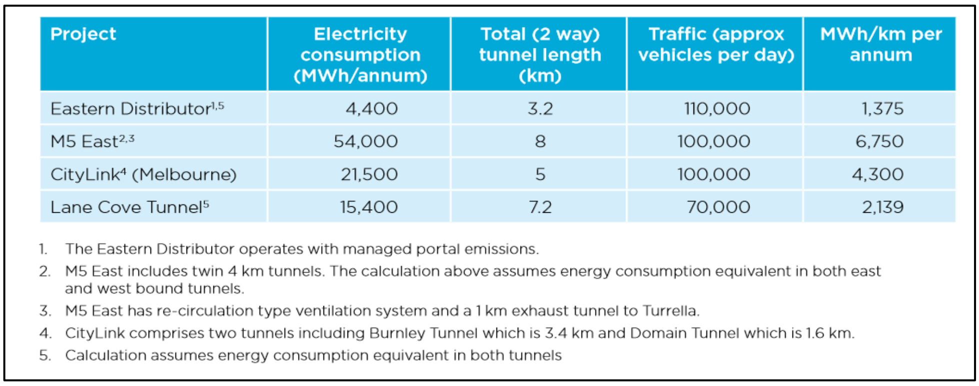


Figure 4 Breakdown of road tunnel energy consumption

The energy consumption specifications for the tunnel's jet fans and axial fans will be used to assess the project model's energy consumption analysis. Table 4 presents a comparison of electricity consumption rates for certain road tunnels in NSW and Victoria.

Table 4 Tunnel electricity consumption (RMS, 2014)



Project	Electricity consumption (MWh/annum)	Total (2 way) tunnel length (km)	Traffic (approx vehicles per day)	MWh/km per annum
Eastern Distributor[1,5]	4,400	3.2	110,000	1,375
M5 East[2,3]	54,000	8	100,000	6,750
CityLink[4] (Melbourne)	21,500	5	100,000	4,300
Lane Cove Tunnel[5]	15,400	7.2	70,000	2,139

1. The Eastern Distributor operates with managed portal emissions.
2. M5 East includes twin 4 km tunnels. The calculation above assumes energy consumption equivalent in both east and west bound tunnels.
3. M5 East has re-circulation type ventilation system and a 1 km exhaust tunnel to Turrella.
4. CityLink comprises two tunnels including Burnley Tunnel which is 3.4 km and Domain Tunnel which is 1.6 km.
5. Calculation assumes energy consumption equivalent in both tunnels

3.1.2 Project Model Parameters

The model describes a typical road tunnel in an urban environment with a longitudinal ventilation configuration and one exhaust shaft at each end. The length of the tunnel is 4 km, consisting of two lanes in each direction with no on or off ramps. A schematic of the tunnel chainage with its gradients is presented in Figure 5.

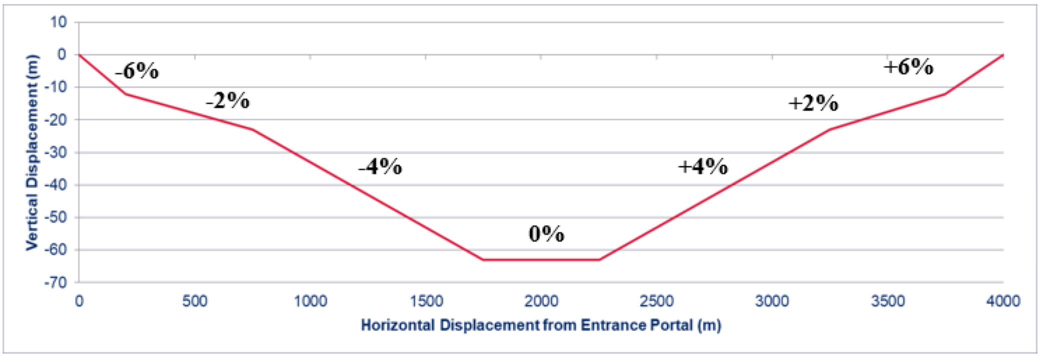


Figure 5 Vertical alignment of project model tunnel

A number of key parameters are required, namely those that describe traffic flow, vehicle characteristics and the tunnel geometry. Normal operation traffic flow profiles were derived from tolling data from a Sydney urban road tunnel. Table 5 provides a summary of the vehicle characteristics used in the project model. The main vehicle characteristics are the vehicle cross-sectional (frontal) area, aerodynamic drag coefficient and vehicle type distribution. The weighted average characteristics represent a typical vehicle that passes through the tunnel. Table 6 provides a summary of the important tunnel geometry parameters in the project model.

Table 5 Project model vehicle characteristics

Vehicle Type	Vehicle Cross-sectional Area (m^2)	Aerodynamic Drag Coefficient (-)	Vehicle Type Distribution
Passenger Car	2.5	0.4	72%
Light Duty Vehicle	5	0.6	12%
Heavy Goods Vehicle	7	0.8	16%
Weighted Average	**3.53**	**0.49**	

Table 6 Project model tunnel geometry and other parameters

Parameter	Value	Parameter	Value
Tunnel length	4,000 m	Cross-Sectional Area	80 m^2
Tunnel height	8 m	Perimeter	36 m
Road width	10 m	Wall surface friction factor	0.035
Hydraulic Diameter	8.9 m	Density of air	1.204 kg/m^3
Number of lanes	2		

3.2 Future trends of the NSW Fleet incorporating AFVs

A detailed analysis was undertaken to assess the future trends of the NSW vehicle fleet incorporating AFVs. Three scenarios were determined for this study:

- the 'base case', built on the NSW fleet forecast with the currently experienced trends in AFVs
- the 'expected case', with AFV forecasts derived from Future Transport 2056 (2019); and
- an 'accelerated case', based on Energeia's (2018) accelerated intervention case.

All three fleet forecast scenarios were created using the NSW fleet forecast (as presented in Section 2.2) with the inclusion of the respective AFV statistics derived from each source. An example for the 'base case' in the year 2020 is presented in Table 7 which includes the proportion of the fleet that are AFVs. The updated NSW fleet forecasts are presented as graphs in Section 4 of this paper.

Table 7 NSW fleet composition for 2020, 'base case' scenario

Vehicle	Fuel	Year	Pre Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6	Total
PC	**Petrol**	2020	0.6%	2.66%	3.52%	12.90%	40.41%	22.39%	0.00%	100%
	Diesel		0.02%	0.05%	0.61%	-	8.14%	7.92%	0.00%	
	AFV		0.78%							
LDV	**Petrol**		3.8%	2.27%	2.26%	6.43%	9.69%	4.33%	0.00%	100%
	Diesel		0.78%	0.37%	2.81%	-	35.62%	30.77%	0.00%	
	AFV		0.84%							
HDV	**Diesel**		11.8%	2.44%	0.00%	11.51%	15.76%	53.61%	0.00%	100%
	AFV		4.84%							

3.3 Validation of the RMS NSW emissions estimation Model

The validation study processed 12 months of air quality, traffic and temperature data from January to December 2018, and incorporated over 300 million data points. The fleet composition was used in conjunction with PIARC (2019) base emissions rates to calculate the expected emissions from a certain number of vehicles travelling through the tunnel. A flowchart of the validation study inputs, and method is presented in Figure 6.

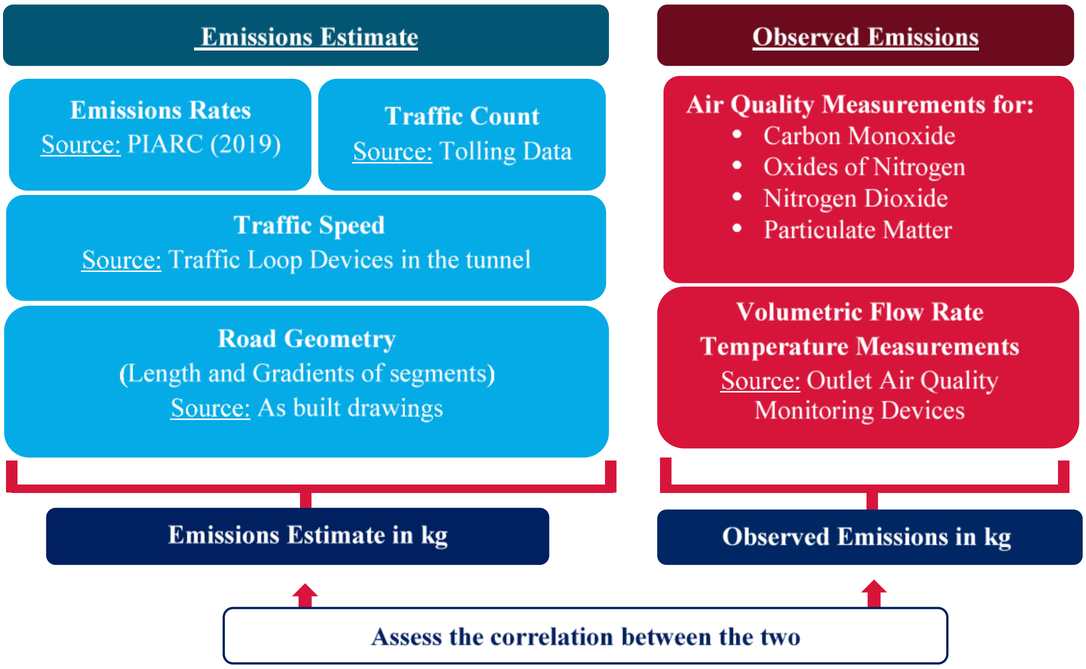


Figure 6 Validation Study Inputs and Methodology

3.3.1 Estimation of Vehicle Emissions

The road tunnel is divided into a series of aerodynamic sections, each with its own road gradient and length as well as specific measured average speeds and traffic counts. Each direction of the tunnel, eastbound and westbound, was assessed separately.

The equation for the total mass of emissions generated in the tunnel per hour is:

$$G_{tun} = \sum_{k=1}^{z} \left\{ \sum_{j=1}^{y} \left(\sum_{i=1}^{x} q\left(v_{(j,k)}, t_k\right) \times w_{i,j} \right) \right\} \left(\frac{n_{category} \times l_k}{v_{(j,k)}} \right) \tag{2}$$

G_{tun} = Total emissions generation of a pollutant along the length of the tunnel [g/h]
$q(v,t)_{j,k}$ = Base emission rate from PIARC (2019), depending on the average speed and road gradient in the section [g/h] or [m^2/h]
$v_{j,k}$ = Hourly average speed of each vehicle category (PC, LDV, HGV) in each tunnel section
t_k = Road gradient within a tunnel section
$w_{i,j}$ = Weighting of a vehicle class' Euro Standard, determined from fleet composition.
$n_{category}$ = Number of vehicles in the tunnel from a vehicle category (i.e. PC, LDV or HGV)
l_k = Length of tunnel section

- For x number of Euro standards (Pre-Euro, Euro 1 … Euro 6)
- For y number of vehicle classes (e.g. PC Petrol, LDV Diesel, etc.)
- For z number of sections in each tunnel carriageway (eastbound or westbound)

The mass of estimated emissions (G_{tun}) allows for a comparison to the measured emissions in a comparable "grams per hour" metric.

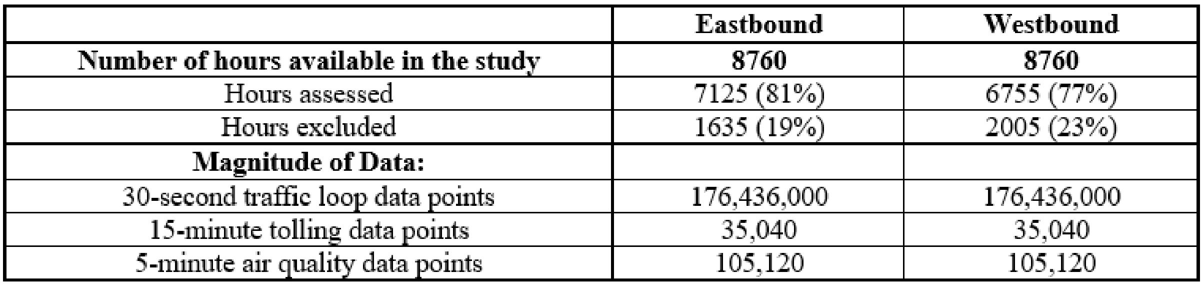
3.3.2 Determining the Observed Emissions

The observational aspect of the validation study utilised the sensors within a Sydney urban road tunnel to record the real-world conditions. For confidentiality reasons the tunnel name cannot be disclosed. The observed emissions from the ventilation outlets were recorded in five-minute intervals across the twelve months of 2018. Measurements were then aggregated into hourly periods. The parameters measured at the tunnel's ventilation outlet's air quality monitoring stations and analysed in this validation assessment are:

- Carbon Monoxide (CO)
- Oxides of Nitrogen (NO_x)
- Nitrogen Dioxide (NO_2)
- Particulate Matter (PM_{10})
- Stack Temperature
- Volumetric Flowrate

A summary of the data quality for the validation study is presented in Table 8.

Table 8 Summary of data quality



	Eastbound	Westbound
Number of hours available in the study	**8760**	**8760**
Hours assessed	7125 (81%)	6755 (77%)
Hours excluded	1635 (19%)	2005 (23%)
Magnitude of Data:		
30-second traffic loop data points	176,436,000	176,436,000
15-minute tolling data points	35,040	35,040
5-minute air quality data points	105,120	105,120

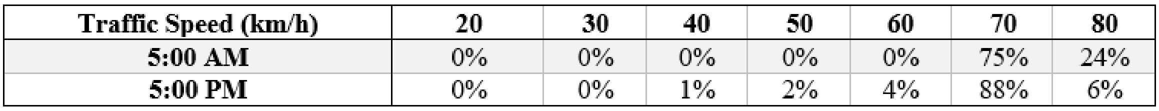
3.4 Impact Assessment of Changes in the NSW Fleet

For the impact assessment of changes in the NSW fleet, the following pollutant design constraints were applied:

- CO: 0.03 g/m3 at the tunnel exit portal
- NO_2: 0.00188 g/m3 (1 ppm) at the tunnel exit portal
- PM10: 0.00106 g/m3 at the tunnel exit portal

For the normal operation assessment, a probability distribution profile of average speeds was created, to reflect the proportion of speeds present in the validation study road tunnel for each hour of the day. The following probabilities (Table 9) are an example of two hours (5 AM and 5 PM).

Table 9 Probability distribution of traffic speeds for 5 AM and 5 PM (example)



Traffic Speed (km/h)	20	30	40	50	60	70	80
5:00 AM	0%	0%	0%	0%	0%	75%	24%
5:00 PM	0%	0%	1%	2%	4%	88%	6%

The weighted average emissions generated per second value were then divided by the pollutant design concentration to calculate the required volumetric flowrate. By calculating the required volumetric flowrate for each pollutant at each hour of the day, a daily ventilation profile could be derived. The process was repeated for each year 2020 to 2040 and each NSW fleet scenario.

The peak-scenario ventilation assessment sought to determine the dominant air quality criterion (management of pollutant concentration or zero net portal emissions) during peak traffic capacity scenarios. The peak-scenario traffic flow profiles (Table 10) were used to determine the total emissions generated at each vehicle speed.

Table 10 Peak-Scenario Traffic Flow Profile

Traffic Speed (km/h)	20	30	40	50	60	70	80
Traffic Flow (veh/lane/h)	2700	3300	3720	3980	4100	4120	3800
Traffic Density (veh/lane/km)	135	110	93	80	68	59	48

3.4.1 Calculation of the Piston Effect for Vehicle Induced Airflow in Road Tunnels

A detailed derivation was undertaken from first principles for the calculation of the vehicle-induced inflow of fresh air from tunnel entrance portal, a phenomenon known as the 'piston effect'. The piston pressure change equation is:

$$\Delta p_{piston} = \frac{1}{2}\rho \frac{c_d \alpha}{(1-\alpha)^2}(v_{vehicle} - v_{tunnel})^2 \tag{3}$$

where c_d is the coefficient of drag, ρ is the density of air, α is the blockage ratio (Vehicle area divided by tunnel area: A_V/A_T) and $v_{vehicle}$ is the average speed of vehicles travelling through the tunnel. For the air flow between the entrance portal and exit portal of a tunnel, the change in pressure from the movement of air is expressed as:

$$\Delta p_{12} = \left(\xi_1 + \lambda \frac{l_{12}}{d_h} + \xi_2\right)\frac{\rho {v_{tunnel}}^2}{2} \tag{4}$$

where location 1 is the tunnel entrance and location 2 is the tunnel exit, Δp_{12} is the change in pressure from the tunnel entrance to the tunnel exit, ξ_1 is the friction factor at the tunnel entrance, ξ_2 is the friction factor at the tunnel exit, λ is the Darcy-Weisbach wall surface friction factor, l_{12} is the tunnel length from entrance to exit and d_h is the tunnel hydraulic diameter.

The two equations Eq. (3) and Eq. (4) are solved simultaneously to determine the "operating condition" and the air velocity, which can be converted to the volumetric airflow given the tunnel cross-sectional area. A comparison between an arbitrary fan curve from an industrial fan supplier (Schotz, 2019) and the project model's peak-scenario "piston effect curve" for vehicles travelling at different speeds is presented in Figure 7. The piston airflow was determined in practice using Microsoft Excel's Solver function to set the difference between the tunnel resistance pressure change and piston effect pressure change to zero.

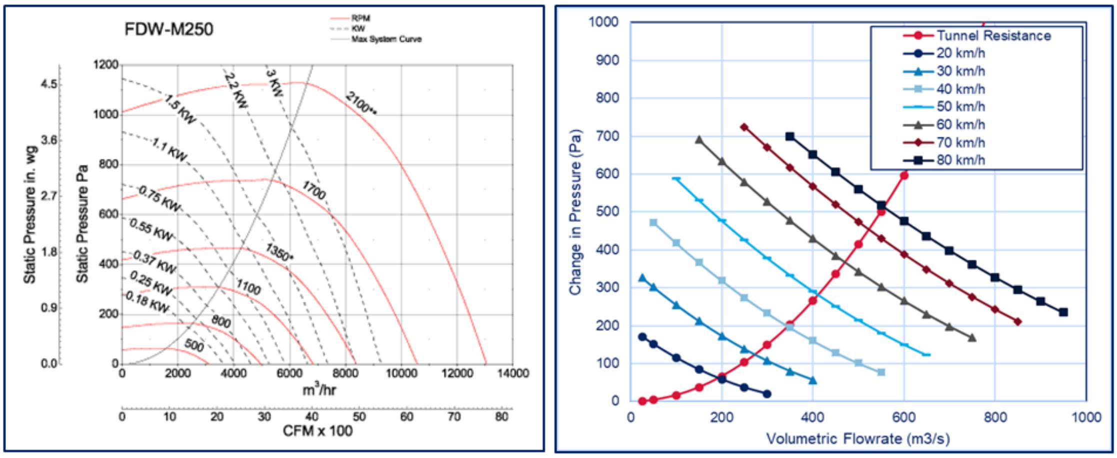


Figure 7 **(a) An arbitrary fan curve relating flowrate and static pressure and (b) A 'piston curve' from the project model, relating volumetric flowrate to change in pressure.**

3.5 Impact Assessment of Changes in Air Quality Criteria

The methodology for the impact assessment of changes in air quality criteria closely followed the methodology in Section 3.4. Instead of assessing the changes in the vehicle fleet, the ‘expected case’ scenario for the NSW fleet was kept constant as the model’s fleet input and the pollutant concentration criteria at the tunnel exit were varied.

For the assessment only the variation in concentrations of NO_2 at the exit portal was addressed. For each NO_2 exit-portal concentration, the following were determined: the energy consumed by the ventilation system if portal emissions were allowed across the whole day, and the energy consumed by the ventilation system if portal emissions were allowed only during off-peak periods (8pm to 5am inclusive). Figure 8 shows the methodology to determine the energy consumption each hour of the day under the normal operations traffic scenario for the ‘expected case’ NSW fleet.

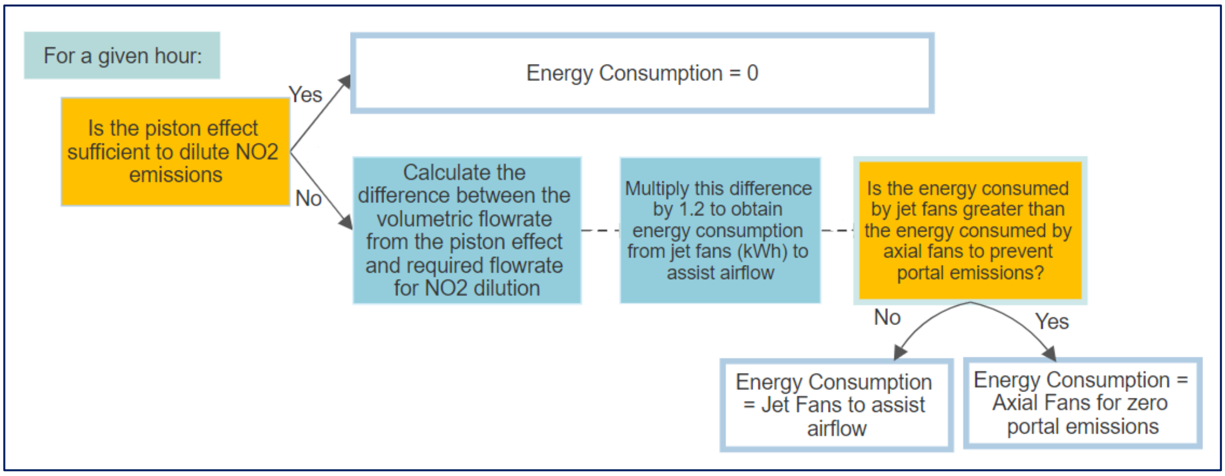


Figure 8 Methodology to determine the energy consumption for each hour of the day

The number of hours per 24-hour period (across the whole day) and 10-hour period (during off-peak hours) whereby the vehicle piston effect sufficiently induced an acceptable volumetric airflow to meet a multiple of the background NO_2 concentration was plotted for each year from 2020 to 2040. An appropriate NO_2 exit portal concentration was determined.

5 Results and Discussion

The methodology in Section 4 was conducted over the course of eighteen months. The results and ensuing discussion are presented in this section in relation to each of the five research questions.

5.1 Research Qu. 1: What are the future trends in the NSW vehicle fleet?

The future trends in the NSW vehicle fleet were modelled as three scenarios, based on the uptake of alternative fuel vehicles each year from 2020 to 2040. The three figures show the NSW fleet composition for the 'base case', 'expected case' and 'accelerated case' scenarios.

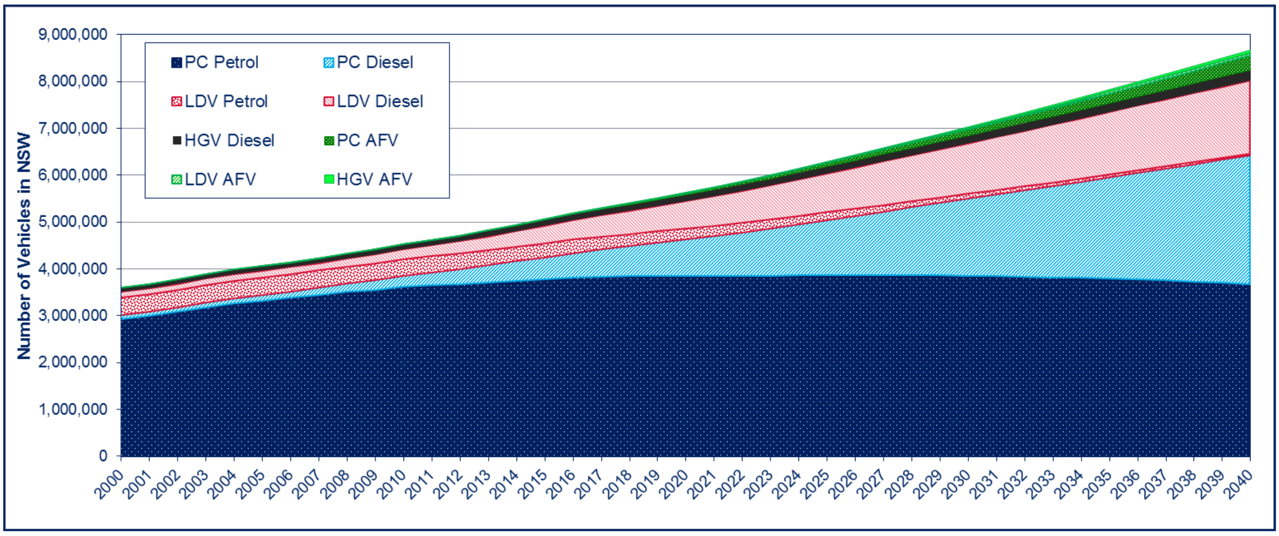


Figure 9 **NSW fleet forecast - Scenario 1: 'base case', 2000 to 2040**

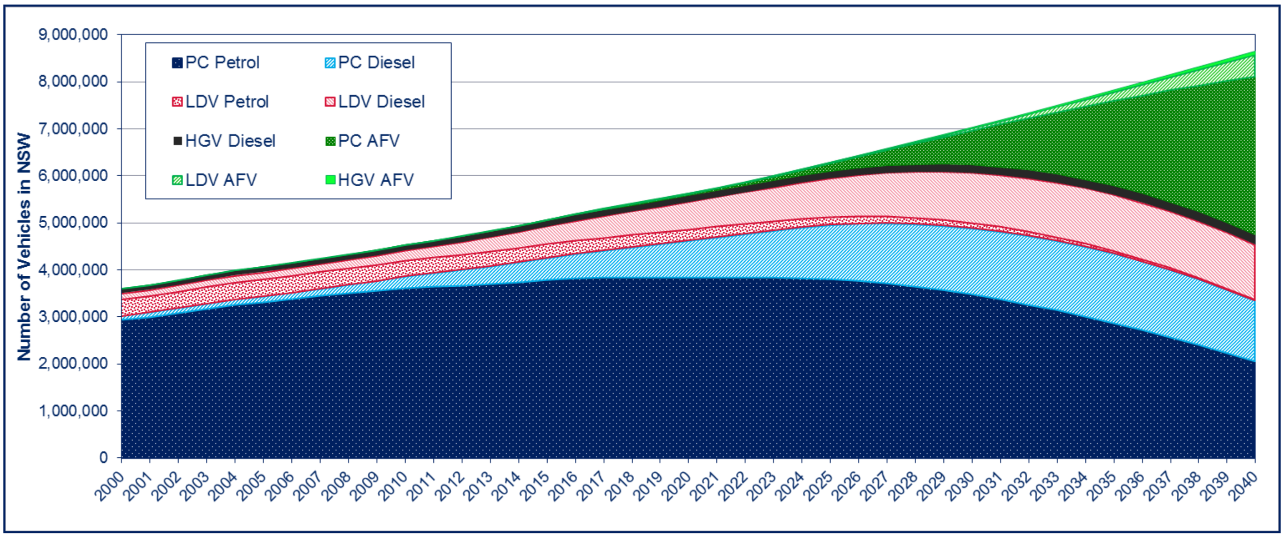


Figure 10 **NSW fleet forecast - Scenario 2: 'expected case', 2000 to 2040**

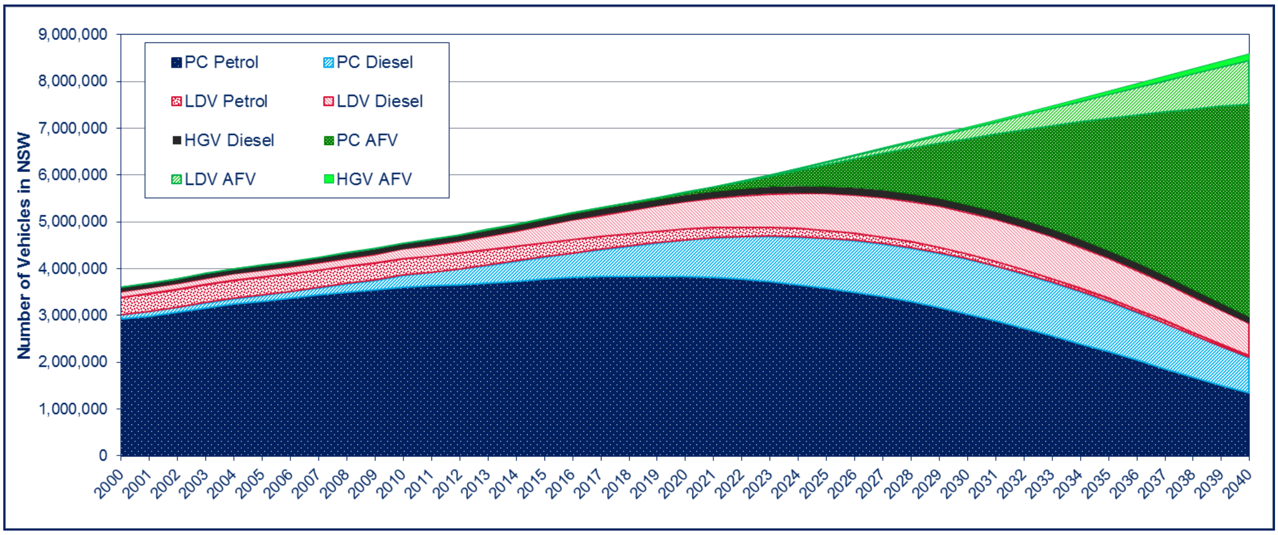


Figure 11 **NSW fleet forecast - Scenario 3: ‘accelerated case’, 2000 to 2040**

Each forecast attempts to account for different factors that influence the growth of AFVs such as model availability, charging stations, government policies, subsidies and technology improvements. However, what each of the NSW fleet forecast scenarios highlight is that a considerable portion of the fleet are still internal combustion engine (ICE) vehicles in 2040. This is true even for the ‘accelerated case’ whereby approximately 3 million vehicles are anticipated to remain in the fleet in 2040.

The trends of growth and attrition rates were assumed to remain the same for future (ICE) vehicles under the current model. This assumption could change, whereby an increase in the attrition rate of older vehicles may be seen as new AFV models are introduced to the market. Conversely, a supply limitation of AFVs due to market could cause vehicle owners to retain their vehicles for longer.

Another key assumption in the model is the constant growth of the total number of vehicles from 2020 to 2040. To ensure that this assumption was appropriate, the year-on-year growth rate and total volume of the NSW fleet was compared with the NSW population (NSW Department of Planning, 2019). These are plotted in Figure 12. A relationship between the growth rates of the vehicle fleet and NSW population is present in the ratio of approximately 2:1.

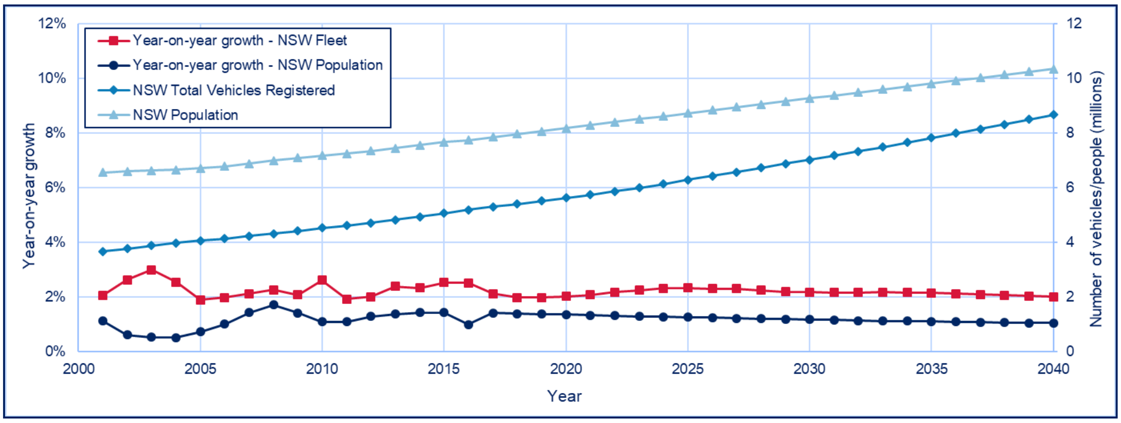


Figure 12 **Growth rate and total volume of the NSW vehicle fleet and NSW population.**

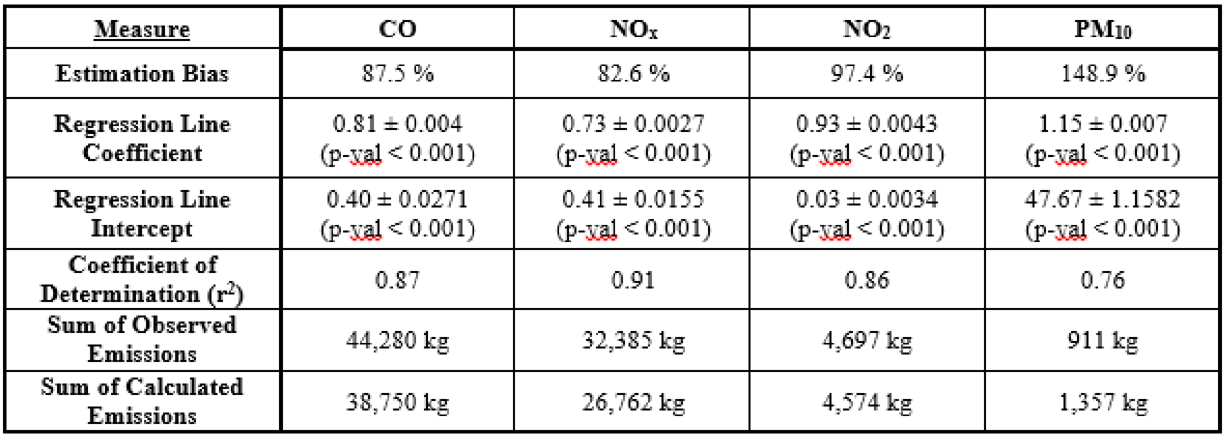
5.2 Research Qu. 2: Does the NSW emissions estimation model correlate with tunnel data?

5.2.1 Validation Study Results

A summary of the key statistics for each pollutant (CO, NO_x, NO_2 and PM_{10}) is presented in Table 11 for the eastbound direction and Table 12 for the westbound direction. The estimation bias is the ratio of estimated emissions over observed emissions. An estimation bias greater than 100% indicates the model overestimated the observed emissions.

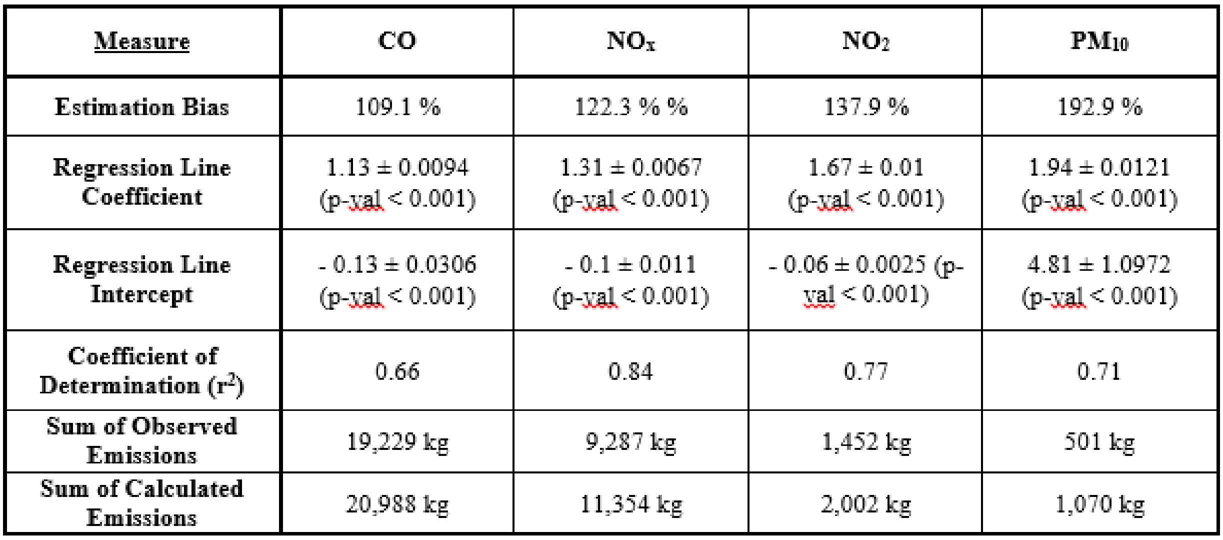
For brevity, only the scatter plot for the calculated vs. observed NO_2 emissions is presented as the "pollutant of interest". Each point in Figure 13 represents one hour. The red line is the linear regression line with 95% confidence interval bounds. The black dashed 45° line represents equality between the observed and calculated emissions. Data points above the black line represent an overestimation by the model, and below the line represents and underestimation by the model.

Table 11 Validation Study Key Statistics – Eastbound



Measure	CO	NO_x	NO_2	PM_{10}
Estimation Bias	87.5 %	82.6 %	97.4 %	148.9 %
Regression Line Coefficient	0.81 ± 0.004 (p-val < 0.001)	0.73 ± 0.0027 (p-val < 0.001)	0.93 ± 0.0043 (p-val < 0.001)	1.15 ± 0.007 (p-val < 0.001)
Regression Line Intercept	0.40 ± 0.0271 (p-val < 0.001)	0.41 ± 0.0155 (p-val < 0.001)	0.03 ± 0.0034 (p-val < 0.001)	47.67 ± 1.1582 (p-val < 0.001)
Coefficient of Determination (r^2)	0.87	0.91	0.86	0.76
Sum of Observed Emissions	44,280 kg	32,385 kg	4,697 kg	911 kg
Sum of Calculated Emissions	38,750 kg	26,762 kg	4,574 kg	1,357 kg

Table 12 Validation Study Key Statistics – Westbound



Measure	CO	NO_x	NO_2	PM_{10}
Estimation Bias	109.1 %	122.3 % %	137.9 %	192.9 %
Regression Line Coefficient	1.13 ± 0.0094 (p-val < 0.001)	1.31 ± 0.0067 (p-val < 0.001)	1.67 ± 0.01 (p-val < 0.001)	1.94 ± 0.0121 (p-val < 0.001)
Regression Line Intercept	- 0.13 ± 0.0306 (p-val < 0.001)	- 0.1 ± 0.011 (p-val < 0.001)	- 0.06 ± 0.0025 (p-val < 0.001)	4.81 ± 1.0972 (p-val < 0.001)
Coefficient of Determination (r^2)	0.66	0.84	0.77	0.71
Sum of Observed Emissions	19,229 kg	9,287 kg	1,452 kg	501 kg
Sum of Calculated Emissions	20,988 kg	11,354 kg	2,002 kg	1,070 kg

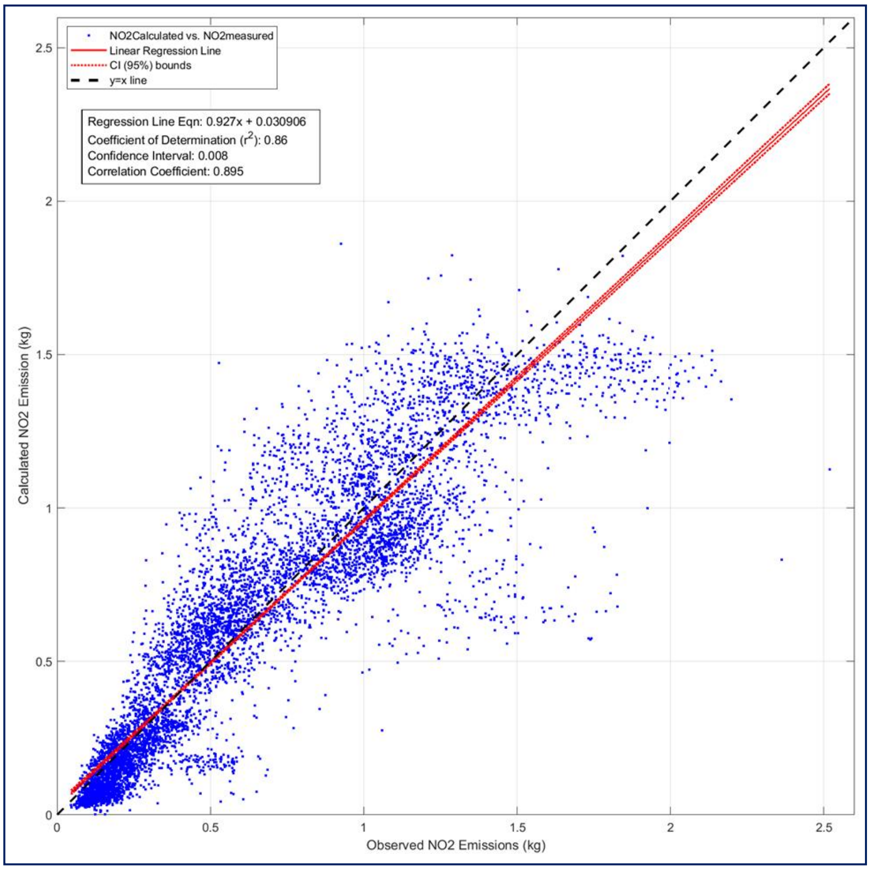


Figure 13 Scatter Plot: Nitrogen Dioxide (NO2) emissions – eastbound direction

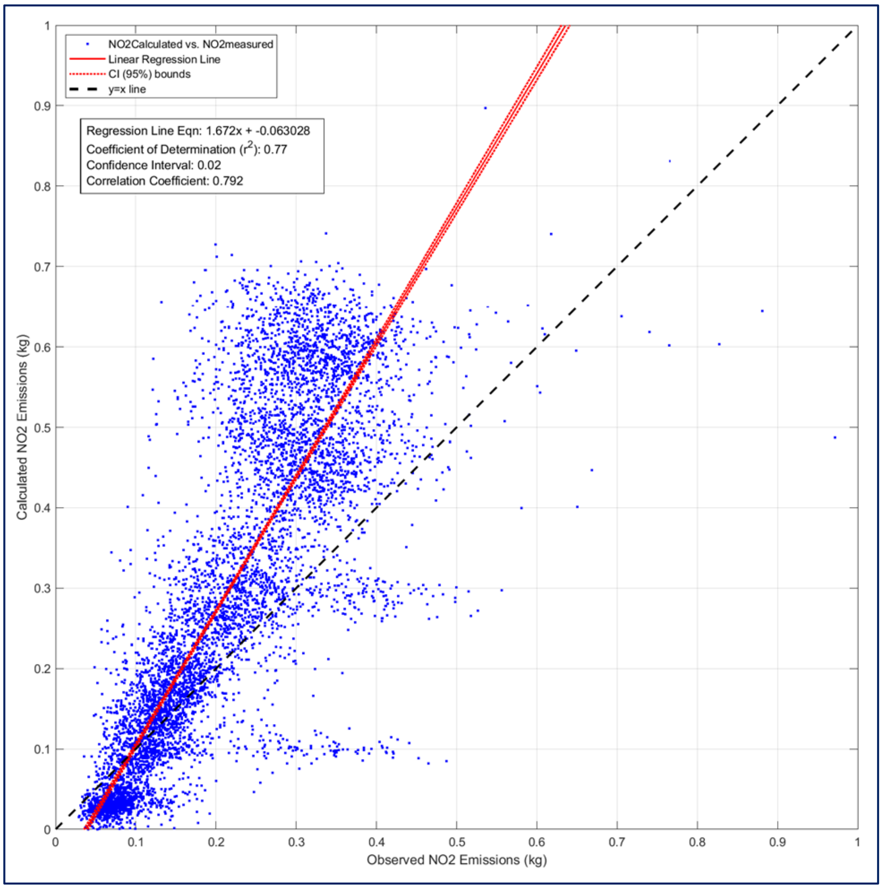
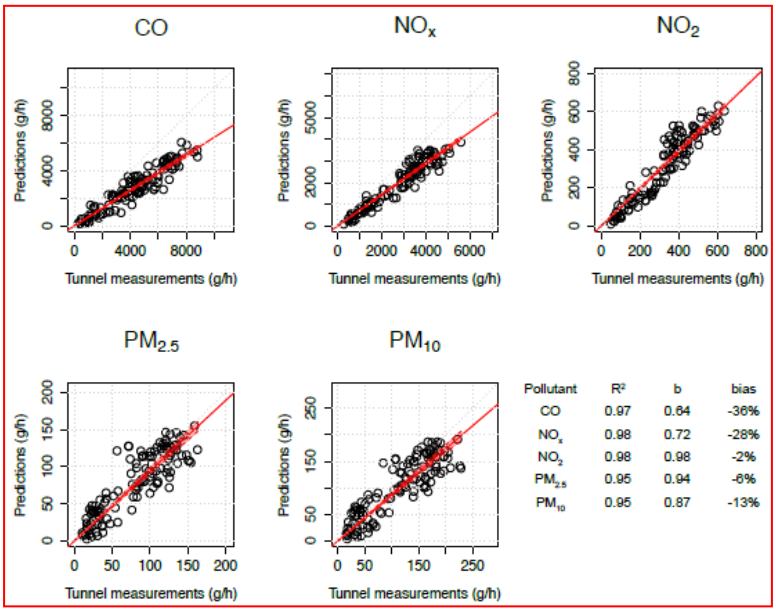


Figure 14 Scatter Plot: Nitrogen Dioxide (NO2) emissions – westbound direction

5.2.2 Discussion

There is a strong correlation between the observed and calculated emissions for all pollutants across the assessment period. A similar validation study, undertaken on a Brisbane road (Smit, Kingston, Wainwright, & Tooker, 2016) sought to validate the previous set of PIARC (2012) emission factors. Smit, et al. (2015) used a vehicle emissions software program and a slightly different methodology for a shorter timeframe. However, the estimation bias for all pollutants are similar to this paper's validation study. A summary of the results from the Smit, et al., (2015) study is presented in Figure 15.



Pollutant	R^2	b	bias
CO	0.97	0.64	-36%
NO_x	0.98	0.72	-28%
NO_2	0.98	0.98	-2%
$PM_{2.5}$	0.95	0.94	-6%
PM_{10}	0.95	0.87	-13%

Figure 15 Results from a similar validation study using a Brisbane road tunnel (Smit, et al., 2015)

The most prominent influence on the emissions model's over or underestimation is road gradient. The eastbound direction is typically uphill (+2% on average) and calculated emissions tend to slightly underestimate whereas estimations for the westbound direction systematically tend to overestimate. The road gradient of the westbound tube is typically downhill (-1% on average). A likely reason for this observation is the unpredictability of driver behaviour when driving downhill, switching between coasting and accelerating. Driving on uphill road gradients requires periodic acceleration.

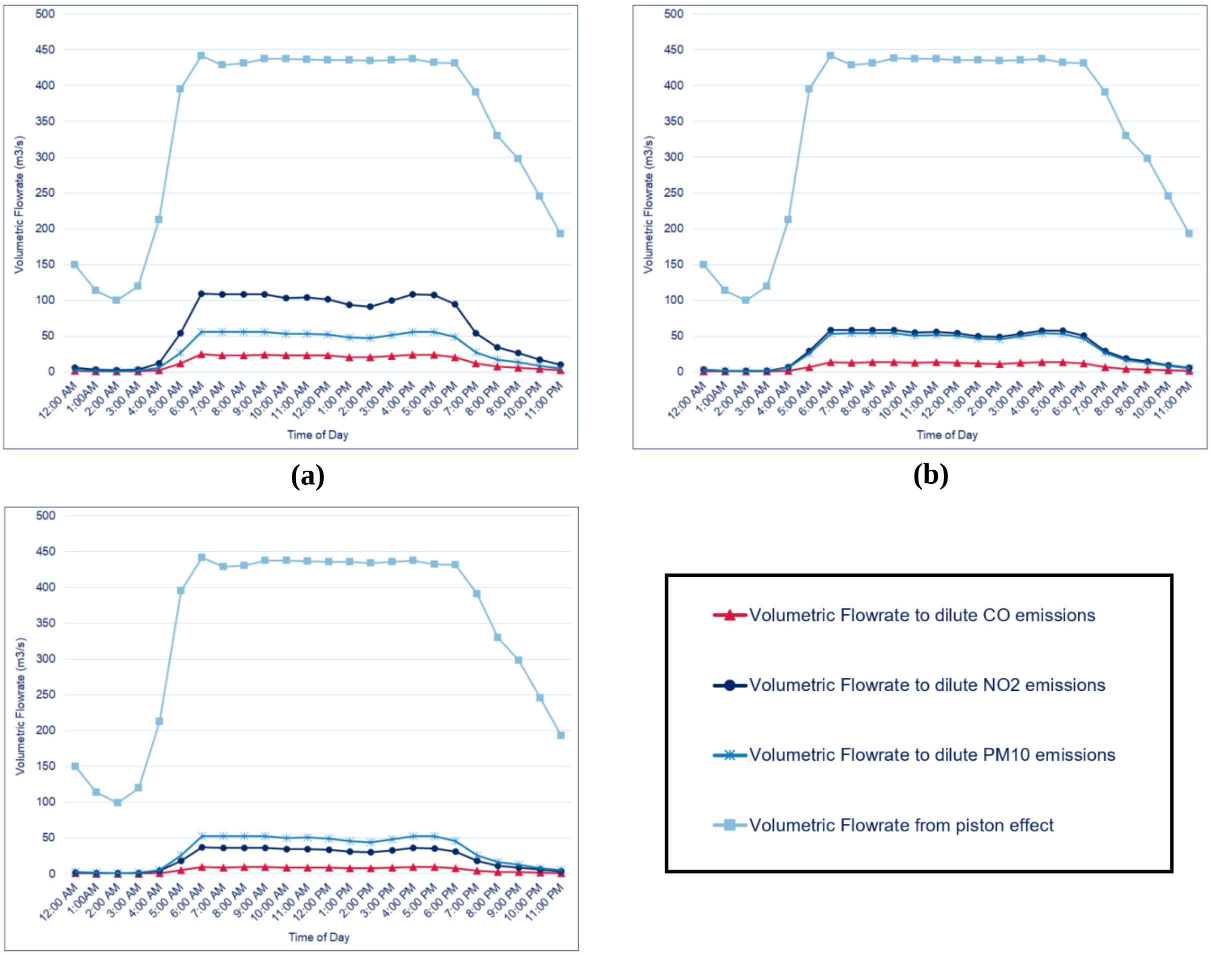
The validation study contains a range of sensitivities and uncertainties: the collection and averaging of traffic speeds and counts, time delays between emissions generation and measurement, changes in the fleet composition, secondary reactions of pollutants, instrumentation error, inaccurate instrument sampling techniques, emissions from natural gas and diesel buses and background air quality assumptions.

5.3 Research Qu. 3: What are the impacts of changes in the NSW fleet on tunnel ventilation energy consumption?

The impacts of changes in the NSW fleet on energy consumption were <u>nil</u>.

The only impacts from changes in the NSW fleet from different growth rates of AFVs are the emissions generated by vehicles. However, with the zero net portal emissions air quality criterion imposed, the induced volumetric airflow from vehicles is greater than the required airflow for emissions dilution. This requires the exhaust axial fans to operate 24 hours per day, even if no vehicles travel through the tunnel. Thus, even as vehicle emissions reduce under each fleet forecast scenario, the energy consumption remains constant.

The normal operations daily profile of volumetric airflow for the ‘base case’ (a), ‘expected case’ (b) and ‘accelerated case’ (c) in the year 2040 are presented in Figure 16. It can clearly be seen that even as the required volumetric flowrate decreases for CO, PM_{10} and NO_2, the volumetric airflow from the piston effect dominates, requiring that axial fans are operated in order to exhaust all air through the ventilation outlet.

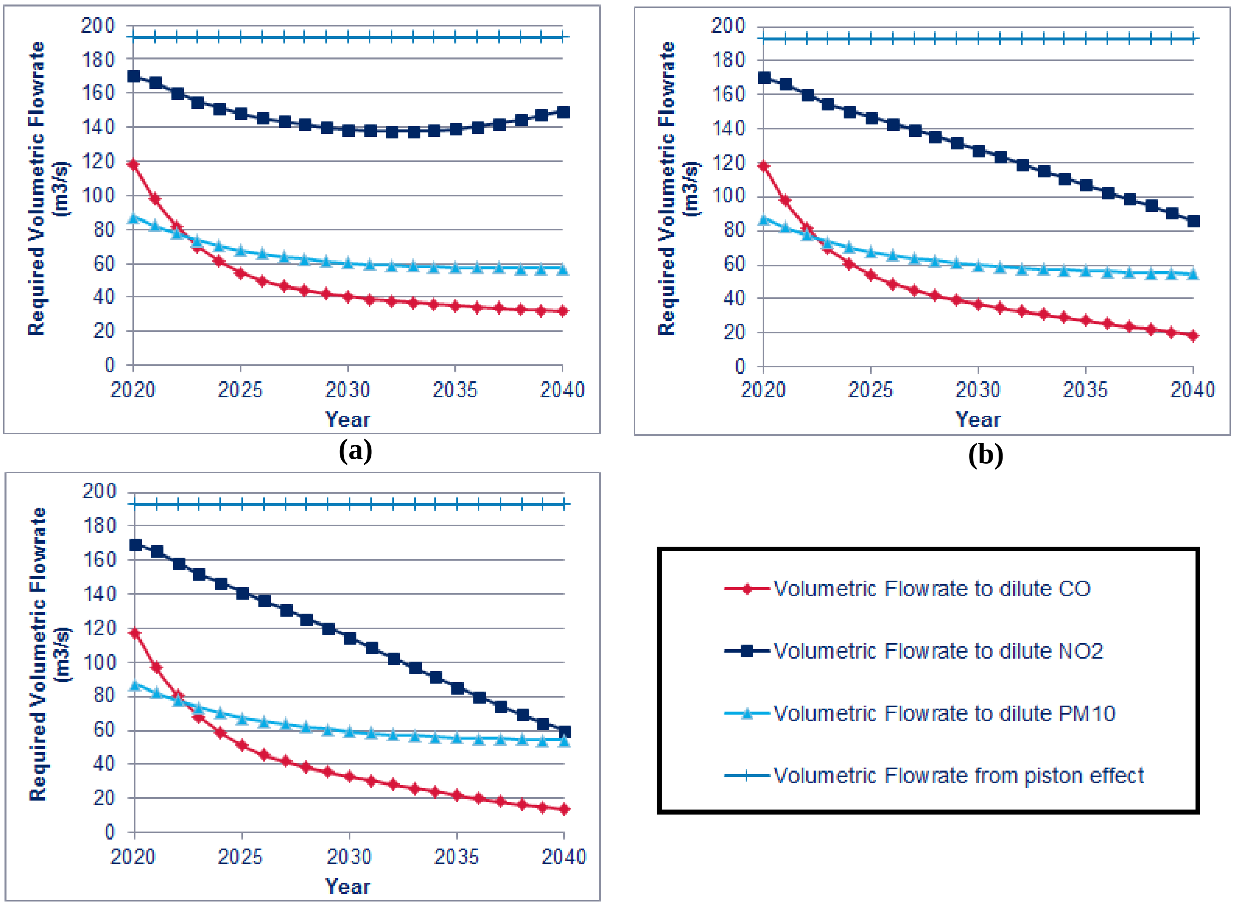


(a) **(b)**

(c)

Figure 16 **Daily profile volumetric flowrate for different requirements for (a) ‘base case’ scenario, (b) ‘expected case’ scenario, (c) ‘accelerated case’ scenario, 2040**

Analysis of the required fresh air demand for peak-traffic at 20 km/h across the three fleet forecast scenarios from 2020 to 2040 provides an insight into changes in the dominant air quality criteria over time. These curves are presented in Figure 17 for the ‘base case’ (a), ‘expected case’ (b) and ‘accelerated case’ (c). Under the base case, Figure 17 (a), an unusual trend occurs where NO_2 emissions decrease to a minimum in 2032 and increase to 2040. This is likely due to the increase in Euro 4, 5 and 6 diesel vehicles in the NSW fleet which generate more NO_2 than older vehicles.



(a)

(b)

(c)

Figure 17 Required volumetric flowrate (m^3/s) for different pollutants for (a) 'base case' scenario, (b) 'expected case' scenario, (c) 'accelerated case' scenario, 2020-2040

5.4 Research Qu. 4: What impacts will variations in air quality criteria on tunnel ventilation energy consumption?

The main variation in air quality criteria on tunnel ventilation energy consumption is the relaxation of the zero net portal emissions criterion. The relaxation of this criterion enables tunnel air to be expelled through the portals. A systematic analysis of different portal exit concentrations was carried out, focussing on NO_2 as the driving pollutant for fresh air demand. The results of the number of hours each day the piston effect was sufficient to ventilate the tunnel are provided in Figure 18. The annual energy consumption from the ventilation system to meet each NO_2 exit-portal concentration is plotted in Figure 19. Note that both analyses were undertaken for one direction in the tunnel. Energy savings metrics would be doubled when considering the whole tunnel.

The exit-portal NO_2 concentration of **0.12ppm** posed the most adequate benefit across all years from 2020 to 2040, balancing energy consumption and ambient concentration goals NEPM (2016). Taking the 0.12ppm NO_2 exit portal concentration as the target, the average annual energy savings from relaxation of the zero net portal emissions requirement would be approximately **12.1 GWh (~83%)** if implemented across the day, or **3.6 GWh (~25%)** if implemented during off-peak hours.

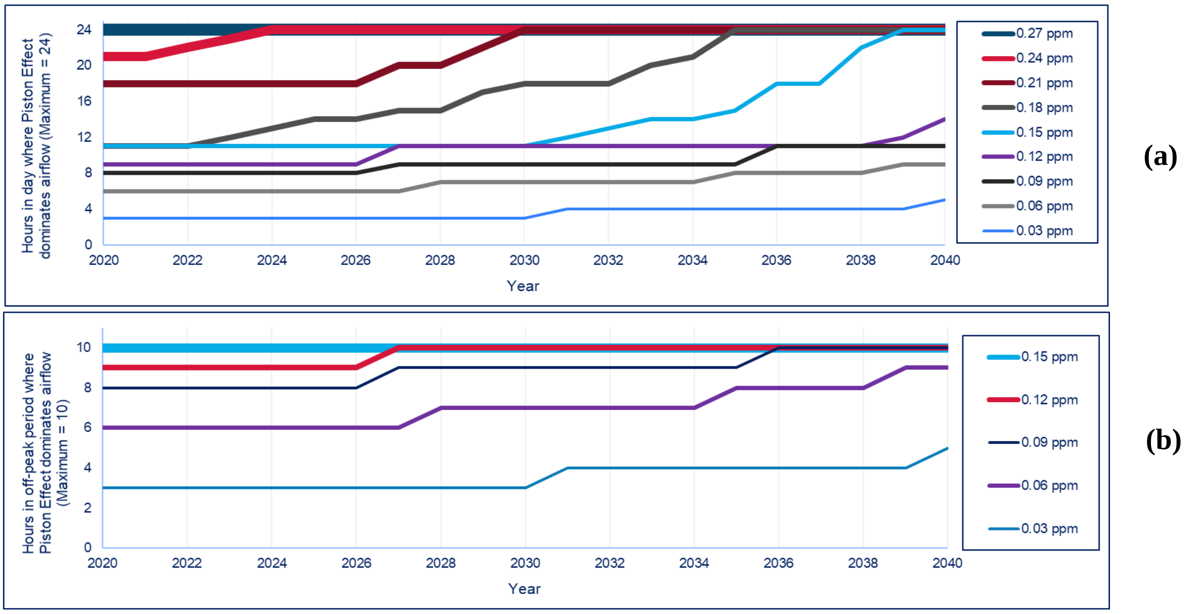


Figure 18 No. of hours per day that the piston effect provides sufficient ventilation when (a) portal emissions occur across the day and (b) portal emissions occur in off-peak hours at different exit-portal NO_2 concentrations (ppm), 2020 to 2040

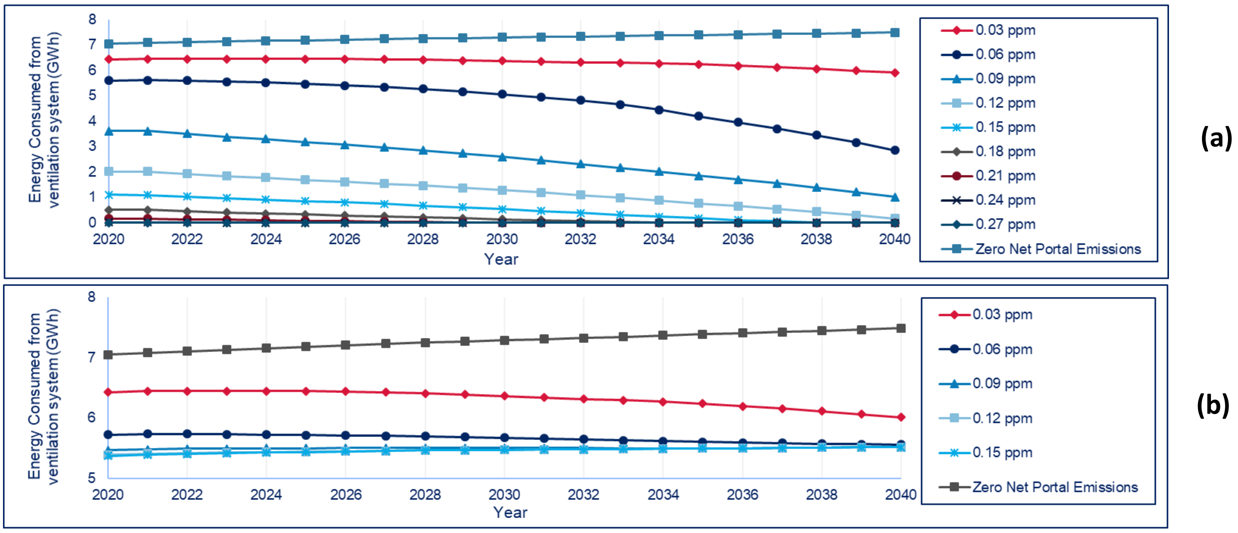


Figure 19 Annual energy consumption for (a) portal emissions across the day and (b) portal emissions in off-peak at different exit-portal NO_2 concentrations (ppm), 2020 to 2040

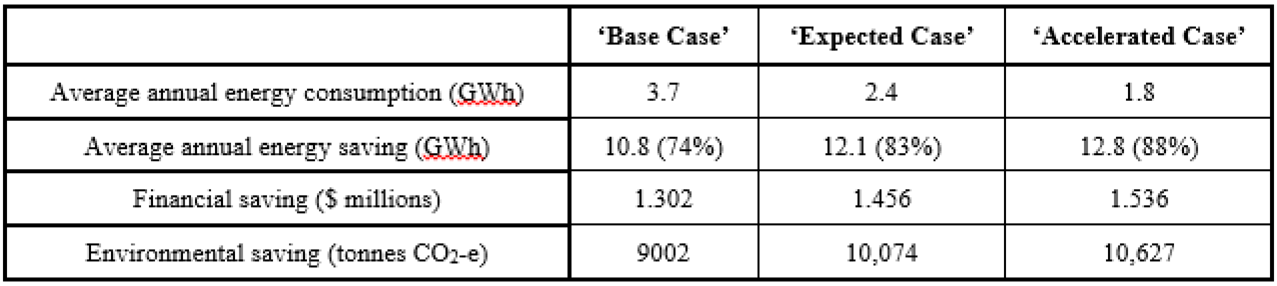
5.5 Research Qu. 5: What are the cumulative impacts of changes in the NSW fleet and air quality criteria on tunnel ventilation energy consumption?

The final question combines the results from sections 5.3 and 5.4. A target of 0.12ppm NO_2 at the tunnel exit was implemented and portal emissions were assumed to occur at all times. Table 13 summarises the average annual energy consumption levels, financial savings and environmental benefits from the relaxation of the zero net portal emissions criterion and changes in the NSW vehicle fleet under normal operating conditions. The cumulative impacts of changes in the NSW fleet are most prominent under the 'accelerated case' whereby no ventilation is required from 2037 onwards.

6 Conclusion

This study investigated the implications of the evolving vehicle fleet on ventilation energy consumption in NSW road tunnels. The annual energy, financial and environmental savings from the relaxation of the zero net portal emissions criterion and changes in the NSW fleet are summarised in Table 13.

Table 13 Summary of implications of changes to air quality criteria and NSW fleet



	‘Base Case’	**‘Expected Case’**	**‘Accelerated Case’**
Average annual energy consumption (GWh)	3.7	2.4	1.8
Average annual energy saving (GWh)	10.8 (74%)	12.1 (83%)	12.8 (88%)
Financial saving ($ millions)	1.302	1.456	1.536
Environmental saving (tonnes CO_2-e)	9002	10,074	10,627

The paper defined a number of secondary research questions that led to the final conclusions. The three forecasts of the NSW vehicle fleet encompass the range of likely AFV growth trends. The ‘accelerated case’ revealed that even under an aggressive growth scenario, a third of the vehicle fleet will comprise of ICE vehicles.

The NSW emissions estimation model validation study was a landmark investigation. It is the first validation study of the recently published PIARC (2019) to have been conducted, and the study’s timeline spans one of the longest investigations for vehicle emissions validation. The key conclusions were:

- A strong correlation existed between the RMS NSW emissions estimation model and observations from a Sydney urban road tunnel.
- NO_2 emissions estimate tended to underestimate observed emissions by approximately 4% on uphill road gradients and overestimate by approximately 38% for downhill gradients

Without changes to the environmental air quality criterion of zero net portal emissions there are no realised energy consumption benefits from the increased adoption of AFVs under the expected and accelerated NSW fleet forecast scenarios.

A key conclusion was the acceptable NO_2 exit-portal concentration of 0.12ppm during periods of portal discharge. Analysis for the ‘expected case’ fleet forecast concluded potential savings of 83% compared to the status quo of zero net portal emissions. Future work would seek to scrutinise, validate and model the numerous assumptions and inputs identified throughout the project. Software such as IDA Tunnel and dispersion modelling may provide greater justification for the relaxation of the zero net portal emissions criterion. An investigation into the relaxation of zero portal emissions for specific NSW road tunnels should be conducted for the significant environmental and financial benefits that exist, especially as the NSW vehicle fleet evolves to include more alternative fuel vehicles.

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