NSW GOVERNMENT

Advisory Committee
on Tunnel Air Quality

TP04:
Road Tunnel Ventilation Systems

Author: Roads and Maritime Services

JULY 2014

Summary

Vehicles on the open road create emissions which are diluted and dispersed through natural surface air flows. Road tunnels create an enclosed space around vehicles where emissions from the vehicles can build up to unacceptable levels without an engineered ventilation system to replace natural surface air flows.

The basic principle of tunnel ventilation is dilution of vehicle emissions by providing fresh air and then removing the exhaust air from the tunnel. The exhaust air can be removed via a portal (a location where the tunnel carriageway opens up to the surrounding environment), via a ventilation outlet (such as a stack), or via a combination of both.

Longitudinal ventilation is the simplest form of engineered ventilation, and involves the introduction of fresh air at the entry portal and the removal of exhaust air out of the exit portal or a ventilation outlet (or a combination of both).

The approach to tunnel ventilation has changed dramatically over time, mainly because of the significant reduction in vehicle emissions. Longitudinal ventilation was once not suitable for longer tunnels due to the need to supply large quantities of fresh air to dilute vehicle emissions. Due it cleaner vehicles, longitudinal ventilation can now readily maintain acceptable air quality in long tunnels, and is generally considered the most efficient and effective tunnel ventilation approach.

All road tunnels built in Australia over the last 20 years have been designed with longitudinal ventilation systems.

1. Introduction to road tunnels and their ventilation needs

Road tunnels have been used for more than two centuries around the world to allow road transport to avoid natural and human made obstacles such as rivers, mountain ranges and dense urban areas.

Road tunnels provide for reduced travel times and improved connectivity of the road network, but their enclosed environment means that some form of ventilation is often required to maintain a safe environment within the tunnel.

This paper considers ventilation of road tunnels in terms of:

1. types of tunnel ventilation,
2. ventilation system operation, and
3. ventilation system energy use.

1.1. What is a road tunnel?

Road tunnels are enclosed roadways with vehicle access restricted to portals. The specific definition of how long a roadway needs to be enclosed to constitute a tunnel varies from source to source.

In NSW a tunnel is defined as an enclosed roadway for a length greater than 120m[1]. This length is used to determine when certain safety systems are required to be installed in the tunnel, such as fire safety systems.

Road tunnels can be uni-directional, meaning traffic within the tunnel moves only in one direction. Usually, two uni-directional tunnels will run side by side to allow for bi-directional traffic flow. Alternatively, road tunnels can be bi-directional, meaning traffic travels in both directions, sharing a common road space.

When considering the need for tunnel ventilation, the requirements are determined by the vehicle emissions in the tunnel and the limits set for pollutant levels in the tunnel by a regulatory or approval authority.

1.2. Why ventilate?

Vehicles on the open road create emissions which are diluted and dispersed through natural surface air flows. Road tunnels create an enclosed space around vehicles where emissions from the vehicles can build up to unacceptable levels without an engineered ventilation system to replace natural surface air flows.

For tunnels up to around 500m in length the natural air flow through the tunnel driven by the movement of vehicles (the 'piston-effect') is normally adequate to manage in-tunnel air quality, and forced ventilation is not required. For longer tunnels forced ventilation in the form of fans may be required at times to ensure that air flow rates are sufficient to maintain in-tunnel air quality to required levels.

The main air quality criteria considered in tunnel ventilation design are carbon monoxide (CO), nitrogen dioxide (NO_2) and visibility. Even though there are other vehicle pollutants to consider, these three criteria are considered to be the most important for health and safety. By managing air quality based on these criteria, other pollutants are managed to well below required levels.

1.3. Principles of tunnel ventilation

The basic principle of tunnel ventilation is the dilution of vehicle emissions by providing fresh air and then removing the exhaust air from the tunnel. The exhaust air can be removed via a portal (a location where the tunnel carriageway opens up to the surrounding environment), via a ventilation outlet (such as a stack), or via a combination of both.

The amount of a given pollutant that is produced in a tunnel per unit time is determined by calculating the total number of vehicles in the tunnel multiplied by the emission rate of each vehicle.

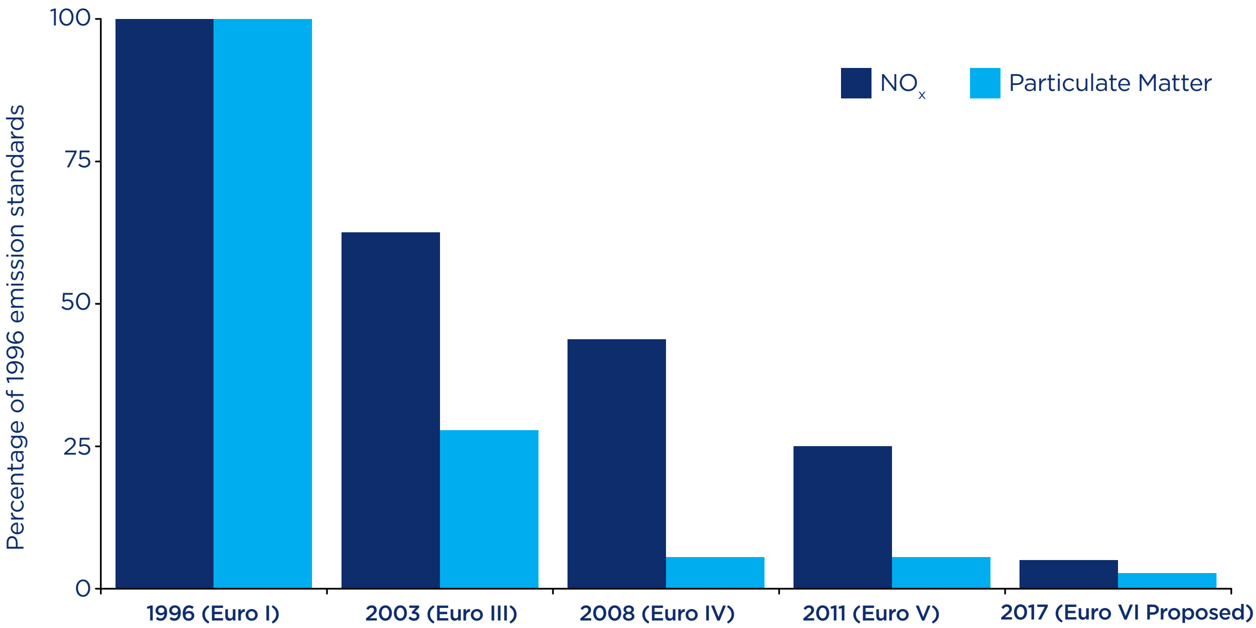
1 Road Tunnel Design Guidelines – Fire Safety, RTA 2006

In terms of ventilation design, the total number of motor vehicles in a tunnel at any one time is primarily determined by the tunnel length, the traffic density and the traffic speed.

The emission rate of a vehicle is dependent on speed and additionally, vehicle type, vehicle age, vehicle condition, traffic conditions and road gradient.

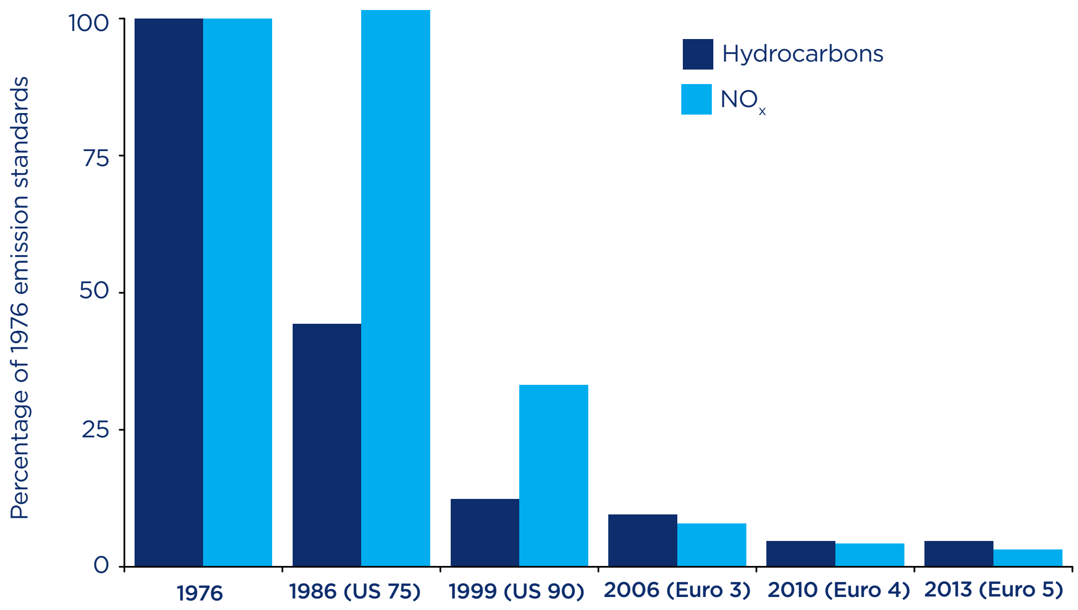
Improvements in vehicle emissions (due to emission-control technology and better fuel quality) have influenced tunnel design requirements. The following figures show the reduction in allowable emissions from different vehicle/engine types in Australia from a given year of manufacture. These figures indicate that there has been up to a fifty-fold reduction in vehicle emissions since the introduction of vehicle emission limits.

Figure 1: Emission standards for new heavy-duty diesel engines, relative to Euro I



1. Introduction to road tunnels and their ventilation needs

Figure 2: Emission standards for new petrol passenger vehicles, relative to Australian Design Rule 27A



2. Types of ventilation system

2.1. Longitudinal ventilation

Longitudinal ventilation in its simplest form comprises of fresh air introduced within the entry portal and exhaust air expelled out of the exit portal. This is shown in Figure 3.

Figure 4 represents the pollution profile along the length of the tunnel. The pollution level increases along the tunnel because this is the direction of air flow, and vehicles continue to generate emissions as they pass from one end to the other. In reality, tunnels in urban areas of Australia are normally graded downhill at the start of the tunnel and then uphill toward the exit, as they generally pass through relatively flat terrain.

The relatively high engine load on the uphill section tends to result in higher exhaust emissions near the end of the tunnel.

The design of a longitudinal ventilation system is dictated by the allowable pollution limit inside the tunnel. The way this is controlled is by ensuring that the volume of fresh air coming into the tunnel at the entry portal adequately dilutes the pollutants. This air volume can be induced by the vehicles, and is sometimes referred to as the 'piston effect'. For longer tunnels the air flow can be supplemented by ventilation fans in cases when the traffic speed is inadequate to generate sufficient portal inflow to keep pollutant levels below the allowable limit.

Figure 3: Longitudinal ventilation

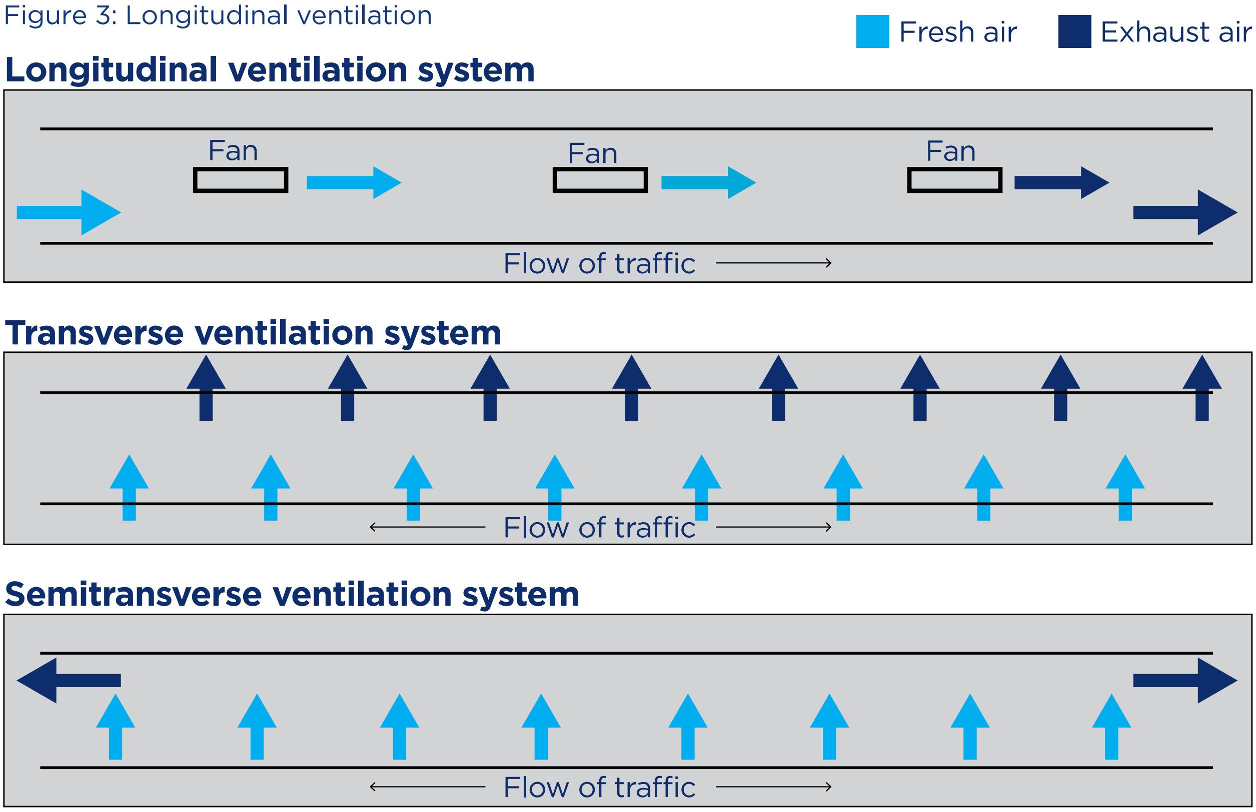
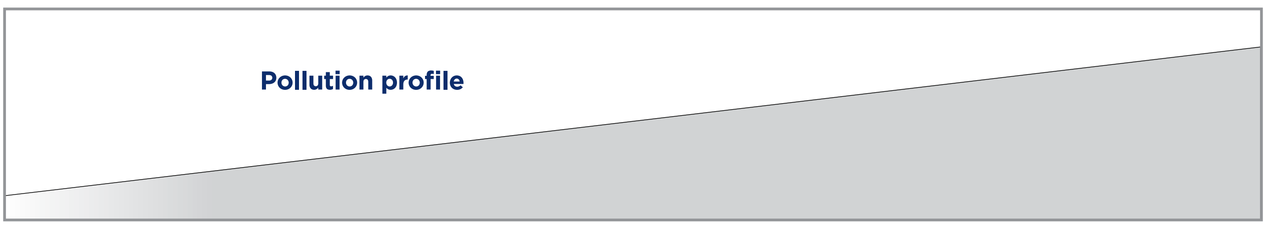


Figure 4: Pollution profile and allowable limit



2. Types of ventilation system

2.2. Transverse ventilation

Transverse ventilation works on the same principle of dilution and removal as longitudinal ventilation, but the supply of fresh air and the removal of exhaust air occurs across the tunnel (ie transversely). This system requires two ducts along the length of the tunnel, one for the supply of fresh air and one for exhausting polluted air (Figure 5). These ducts can be located both at high level or low level in the tunnel, or one at low level and one at high level.

Transverse ventilation has been used in the past where longitudinal ventilation could not adequately manage tunnel pollutant levels due to much higher pollutant levels in tunnels.

Transverse ventilation is also effective in bi-directional tunnels (where vehicles are travelling in both directions in the same tunnel). For these traffic conditions, the piston effect is cancelled out and the pollutant levels are more evenly distributed along the tunnel length.

2.3. Semi-transverse ventilation

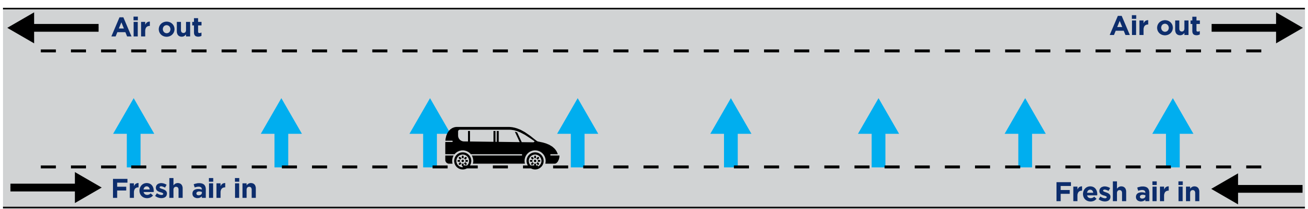
Semi-transverse ventilation is a combination of both longitudinal and transverse ventilation. Fresh air can be supplied from the portals and be continuously exhausted along the tunnel through a duct along the length of the tunnel. Alternatively, fresh air can be continuously supplied along the tunnel via a duct along the length of the tunnel and exhausted out of the tunnel via the portals or a stack.

2.4. Which type of ventilation system do we use?

The approach to tunnel ventilation has changed dramatically over time, mainly because of the significant reduction in vehicle emissions. Longitudinal ventilation was once not suitable for long tunnels due to the need to supply large quantities of fresh air to dilute vehicle emissions. Due to cleaner vehicles, a well-designed longitudinal ventilation system can now easily maintain acceptable air quality in long tunnels and is considered the most efficient and effective tunnel ventilation approach.

All road tunnels built in Australia over the last 20 years have been designed with longitudinal ventilation systems. Sydney Harbour Tunnel (circa 1992) was built with a semi-transverse ventilation system. However, the tunnel is operated as a longitudinal system.

Figure 5: Transverse ventilation



3. Design of tunnel ventilation systems

The operation of a tunnel ventilation system is designed to meet a set of air quality and fire safety performance requirements under it's expected operating scenarios (ie tunnel length and cross section, traffic volumes and mix). The key air quality performance requirements are:

1. In-tunnel air quality criteria
2. External or ambient air quality criteria
3. Other restrictions, such as limited or no portal emissions conditions.

3.1. In-tunnel air quality

The in-tunnel air quality criteria, such as CO, NO_2 and visibility limits, specified for a project will be used by ventilation designers to calculate the system capacity (ie how much fresh air is required to flow through the tunnel under different operating scenarios) to ensure that pollutant concentrations do not exceed the criteria.

Automatic control systems with oversight by a human operator act to ensure continuous ventilation at all times in all major Australian tunnels. These systems monitor air flows, traffic conditions and pollution levels, and adjust the ventilation rates to suit the prevailing conditions in the tunnel.

3.2. Ambient air quality criteria

Exhaust air can be emitted from tunnels via the portals or via a dedicated ventilation stack where improved dispersion is required to maintain ambient air quality.

Technical Paper 5 – 'Road tunnel stack emissions' and Technical Paper 6 – 'Road tunnel portal emissions' cover ambient air quality impacts in more detail.

3.3. Ventilation system capacity

The basis for the design calculation of the tunnel ventilation system capacity is usually the first year of tunnel opening. This is because emissions in the opening year will generally be higher than emissions in subsequent years. This is because improvements in vehicle emissions occur faster than traffic growth rates, meaning overall emissions fall with time (see Technical Paper 1 – 'Trends in motor vehicles and their emissions').

In Europe this has been taken a step further. In the case of the Hafnerberg Tunnel in Zurich (circa 2008);

> *"As a result of the reduction in vehicle emissions with the introduction of stricter emissions standards, the stacks were eliminated from the design… The energy consumption of the ventilation was a strong driver in this decision process"*[2]

3.4. Other restrictions

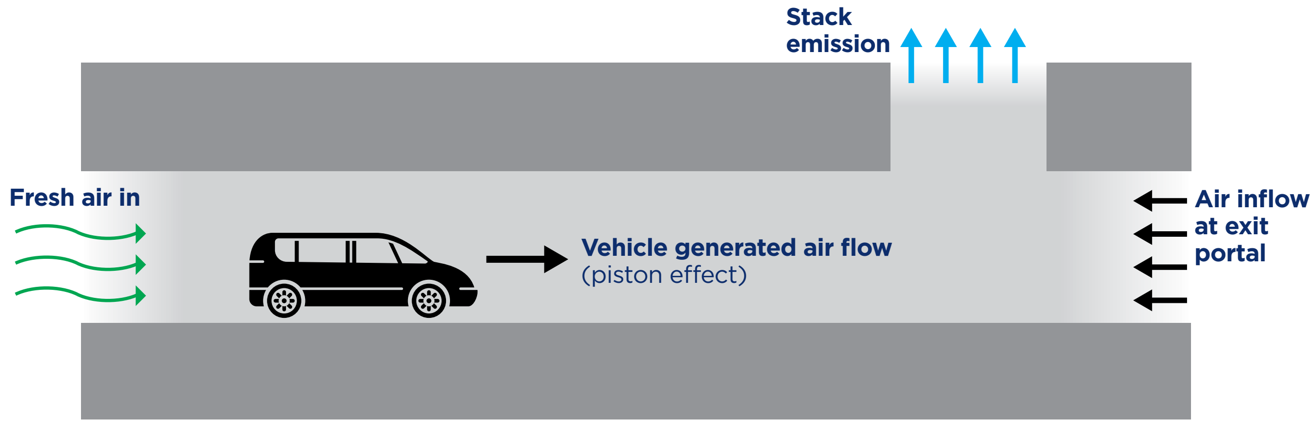
The other key operating restriction for some tunnels in NSW is the requirement for zero portal emissions (ie no exhaust air is allowed to exit the tunnel at the portals). This is required by the Minister's Conditions of Approval for the M5 East, Cross City and Lane Cove tunnels. This was initially applied to the M5 East tunnel as a precaution to protect residents around the tunnel portals. The requirement for zero portal emissions was retained for the Cross City Tunnel and Lane Cove Tunnel.

To meet the zero-portal-emissions condition, all air must be expelled from an elevated ventilation outlet (eg stack), with air drawn in from all portals (Figure 6). In some cases this requires ventilation against the natural direction of air flow due to vehicle movement (ie the piston effect).

2 Road Tunnels: A guide to optimising the air quality impact upon the environment, PIARC Technical Committee C3.3 Road Tunnel Operations, World Road Association.

3. Design of tunnel ventilation systems

Figure 6: Illustration showing tunnel air flow direction to avoid portal emissions



The requirement for zero portal emissions leads to a number of design and operation implications:

1. An alternative ventilation outlet is required, such as a stack.
2. Drawing air in from the exit portal increases the quantity of ventilation air required to be discharged through the stack, and can significantly increase the required size of the stack – leading to increased capital and operating costs and visual impacts.
3. The ventilation system will need to be operated all the time, regardless of whether in-tunnel or ambient air quality warrants this operation.
4. A more complex ventilation system is required. Air will need to flow against the traffic direction in parts of the tunnel, between the stack offtake point and the exit portal. This means operating fans against the natural air flow direction in the tunnel.

4. Energy consumption of tunnel ventilation systems

The largest contributor to the energy consumption of a long tunnel in NSW is the operation of the ventilation system.

With respect to tunnel ventilation, megawatt hours per tunnel kilometre (MWh/km) can be used as an indicator of operational energy consumption.

The measured energy consumption of four road tunnel projects (three in Sydney and one in Melbourne) are provided in Table 1.

This compares energy consumption in megawatt hours (MWh) per year to tunnel length. The data shown provides a range of potential tunnel ventilation and energy consumption scenarios.

When tunnel length and traffic volumes are equal, the key drivers of energy consumption are the complexity of the ventilation system and whether portal emissions are allowed or restricted. For comparative purposes, the M5 East consumes the equivalent energy to nearly 7,400 typical Australian households. The equivalent figure for the Lane Cove Tunnel is slightly more than 2,000 households.

The Eastern Distributor has ventilation stacks at each end of the tunnel that operate as required, however it typically operates with managed portal emissions (ie stack ventilation is not engaged).

The Lane Cove Tunnel has a ventilation stack servicing each end of the tunnel. However, these stacks are located at a considerable distance from the tunnel, and portal emissions are not allowed during operation.

The M5 East has a single ventilation stack with a complex ventilation system and portal emissions are not allowed during operation. This leads to the most inefficient ventilation system design.

Table 1: Tunnel electricity consumption

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