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Low-pressure ventilation system for road tunnel normal operations – West Gate Tunnel

C. Biotto & C. Sahayanathan
Aurecon, Melbourne, Victoria, Australia

C. Jasper & J. Wee
CPBJH, Melbourne, Victoria, Australia

ABSTRACT: Road tunnel ventilation systems face the dual challenge of managing air quality during standard operations and smoke during fire emergencies, and while longitudinal ventilation systems are often combined with smoke extraction, their requirements differ significantly: normal ventilation must move large volumes of air at low pressure, whereas emergency systems require smaller volumes at much higher pressures. At West Gate Tunnel (WGT), two distinct ventilation systems tailored to these specific operational needs were designed, with large, low-speed, low-pressure fans managing normal and congested traffic conditions, and smaller, high-speed, high-pressure axial fans handling emergency scenarios through a single distributed extraction system; this innovative design is estimated to be significantly more efficient than a single high-pressure fan system and not only enhances ventilation effectiveness but also substantially reduces energy usage, setting a precedent for future tunnel ventilation design in urban environments.

1 ROAD TUNNEL VENTILATION IN AUSTRALIA

Tunnels in Australia require ventilation during normal operations, and in uni-directional tunnels this is often achieved through longitudinal ventilation, where air travels in the direction of traffic due to vehicle movement, as shown in Figure 1; however, Australian requirements often mandate that tunnel air must not exit the portals and instead be extracted prior to the exit via mechanical ventilation.

These extraction facilities exhaust the tunnel air at high level through a ventilation shaft to mix it with atmospheric air and improve air quality at ground level to meet ambient air quality limits as described in Longley (2014), Longley (2018) and Sturm (2019). Furthermore, the operators are required to monitor the air quality along the tunnel and maintain the concentration of pollutants (i.e. CO, NO_2, PM10, PM2.5) below a certain threshold as described in Humphrey (2003).

Tunnel ventilation is also used to manage the spread of smoke in case of a fire in the tunnel and often the two functionalities, i.e. air quality and smoke management, are combined into a single ventilation system which is used for both tasks (e.g. Citylink tunnels, M5 East tunnels).

In some tunnels however, the functionalities are split into two ventilation systems, one for air quality purposes and one for fire emergency purposes (e.g. Airport Link tunnels).

In all Australian tunnel where the tunnel ventilation system is combined, the ventilation requirements are met using high-pressure fans, which are energy inefficient, noisy and heavy. This cannot be avoided in fire ventilation systems (and hence for the combined ventilation systems) as the fans need to overcome a higher resistance to extract air from the tunnel without the help of the cars piston effect, especially where a smoke duct is present (e.g. CityLink tunnels).

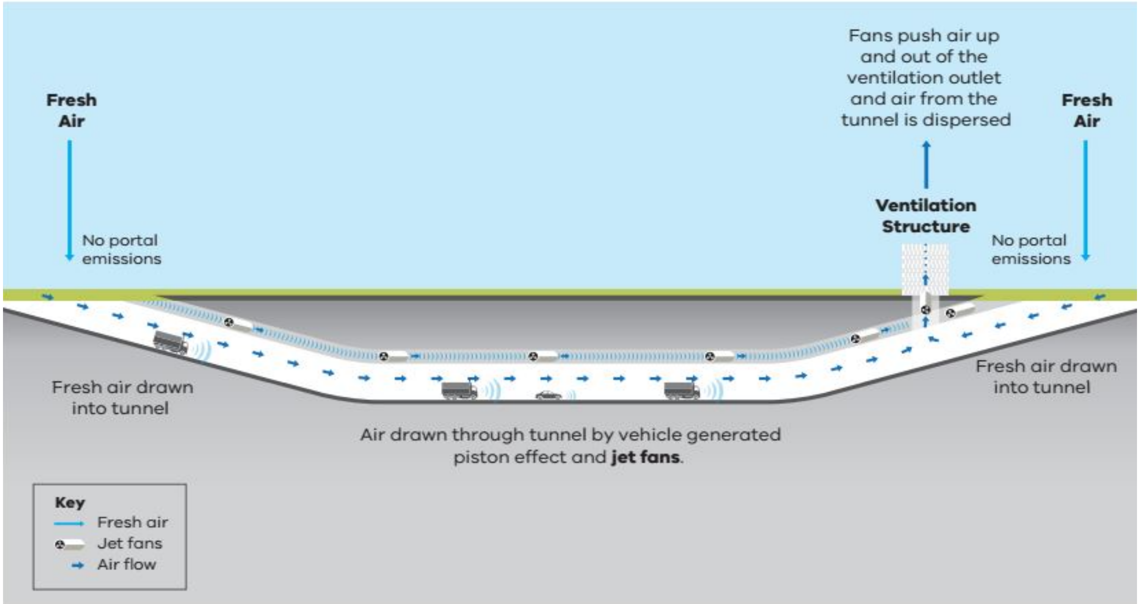


Figure 1. Typical arrangement for longitudinal ventilation with shaft

During most operations, air is naturally pushed along the tunnel to the shafts by the piston effect of moving vehicles, with this flow enhanced by jet fans during slow traffic, the fans only extract air at specific points in the tunnel and push it up the shafts, with the induced flow in the tunnel reducing the required suction-side pressure of the fans. However, the narrow and convoluted air paths in the shafts usually create significant pressure losses, still necessitating high-pressure fans. This limitation was mitigated in WGT and energy efficient, quiet and light low-pressure fans are used for the air quality ventilation system.

2 LOW-PRESSURE FANS IN ROAD TUNNEL VENTILATION

Large low-pressure fans have been historically used in other road tunnels in the world, but not in recent years. Relevant historical examples are:
- Dartford West Tunnel (1963) – 2 fans in 2 shafts, about 175m³/s per fan, as per Kell (1963);
- Dartford East Tunnel (1980) 5 and 6 fans in 2 shafts, about 300m³/s per fan @100Pa, as per Pursall (1982)
- Mersey Kingsway Tunnel (1971) – 4 fans, 6.1m diameter, 108kW, 387m³/s per fan @200Pa, as per Pursall (1973)
- Spier Tunnel (2000) – 1 fan, 6.2m diameter, 87kW, 360m³/s @156Pa as per Van Vemden (2000)
- Ramsgate Tunnel (2000) – 1 fan, 4.0m diameter, 14kW, 100m³/s @95Pa as per Van Vemden (2000)

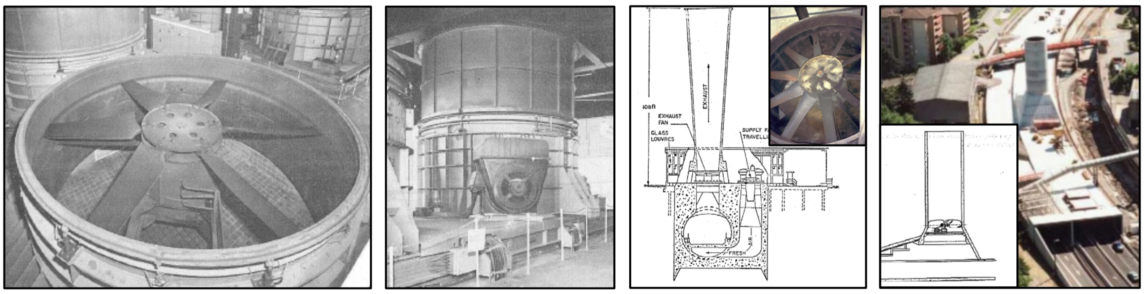

(a) (b) (c) (d)

Figure 2. Low-pressure fans examples: (a, b) Mersey Kingsway Tunnel, (c) Dartford West Tunnel, (d) Spier Tunnel

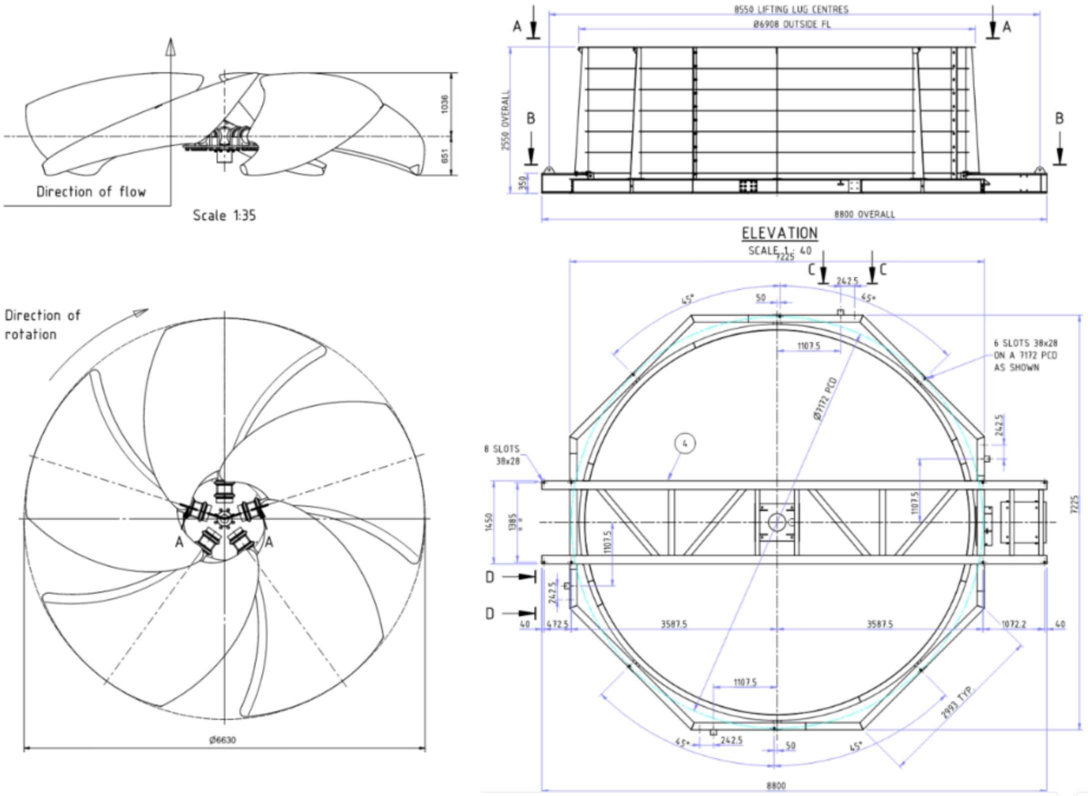


Figure 3. North portal low-pressure fan impeller and casing assemblies

These systems are known for the low noise, long fan life due to lower operating pressures and reduced mechanical strain and low energy consumption. Despite these advantages, low-pressure fan systems have fallen out of favour. Their requirement for large facilities and low-pressure losses poses a challenge, particularly in congested urban areas where road tunnels are often constructed with multiple connections and portals. As a result, more recent projects have opted to combine normal ventilation with high pressure smoke fan systems. However, the recent focus on sustainable infrastructure opens the door for re-evaluating low-pressure fans.

3 AN EFFICIENT VENTILATION SYSTEM FOR THE WEST GATE TUNNEL

3.1 *The West Gate Tunnel project*

The West Gate Tunnel (WGT) Project is a city-shaping project that will deliver a vital alternative to the West Gate Bridge, provide quicker and safer journeys, and remove thousands of trucks off residential streets. The WGT has two separate tunnels: one is 2.79 km long and carries traffic towards Melbourne CBD, known as the Inbound tunnel, the other is a 4.01 km tunnel that carries traffic away from the CBD, known as the Outbound tunnel. Both tunnels share a common civil structure at the northern portal cut and cover (with a full-length dividing wall). Due to their different lengths the two tunnels have separate cut and cover structures at their southern ends, known as the southern portal inbound and southern portal outbound respectively.

3.2 *The air quality ventilation system*

The design team opted for a low-pressure fan system based on several key project requirements. Firstly, the tunnels feature only one entrance and exit for each tube, eliminating slip roads and thereby reducing pressure and airflow losses. Low-pressure fans operate at lower noise levels during regular operations compared to traditional fans, eliminating the need for space and maintenance for sound attenuators. The project requires no emissions at the portals; therefore, the ventilation system is continuously active, pulling large volumes of air through the exit portals. In this respect, low-pressure fans are more energy-efficient than traditional high-pressure alternatives.

Furthermore, the construction programme for the WGT project allowed sufficient time to install the ventilation shafts directly above the cut-and-cover portal, avoiding turns and bends in the airflow path. The use of glass reinformed polymers (GRP) for the low-pressure fans makes them much lighter than steel fans, reducing the static load on the civil infrastructure on the long spans in the portals. The involvement of the operator from the tender design phase focused attention on operational costs, advocating for energy-efficient solutions. Lastly, the WGT shafts were in areas with ample land available to accommodate larger above-ground facilities.

For low-pressure fans at each shaft at the WGT exit portals are Howden SX fans, they are shown in Figure 3 and have the following characteristics:

– North Portal – 4 exhaust fans, 6.63m Ø, 139.6kW, 356m³/s @ 214Pa Static Pressure, 1619kg
– South Portal – 5 exhaust fans, 6.04m Ø, 121.2kW, 267m³/s @ 252Pa Static Pressure, 1502kg

When traffic is travelling above 40km/h the piston effect created by the vehicles, combined with the extraction capabilities of the low-pressure fans, eliminates the need of using jet fans in the tunnel, enhancing the efficiency of the ventilation system with respect to a traditional system.

The project still required a high-pressure fan system for two reasons: the smoke management ventilation has to withstand fire resistance of up to 400°C for two hours, whereas the selected low-pressure fans can only support temperatures up to 250°C, and the project requires a smoke duct for smoke ventilation, leading to high pressure extraction requirements. When in operation, the tunnel ventilation at WGT is estimated to be the most efficient tunnel ventilation in Australia, thanks to this technology, when compared to other main tunnels, as calculated in Biotto (2023).

3.3 *Energy saving benefits*

Fan power is proportional to flow rate and pressure head. Flow rate is fixed by the "no-flow" condition at the portals, leaving little room for reduction through tunnel design. However, optimizing the air path geometry by making it as straight, wide, and short as possible and using quiet fans can reduce pressure losses and lower power. Conservative energy estimates based on the predicted WGT traffic led to a yearly power consumption of 15.5TJ for year 2025 and 16.9TJ for 2031. This is more efficient in comparison to high-pressure fans (420kW for North portal and 300kW for South outbound portal), that would lead to a yearly power consumption of 30.6TJ in 2025 and 33.8TJ in 2031, due to noise attenuation and convoluted air paths. This would require larger electrical facilities and larger infrastructure due to the number of high-speed fans required.

3.4 *Environmental benefits*

Noise generated by low-pressure fans is lower than noise generated by high-pressure fans with the same flowrate, removing the need to install noise attenuator in the system, reducing the pressure losses and minimizing environmental noise. Table 1 compares the noise levels of the air quality low-pressure fans versus the smoke high-pressure fans at WGT.

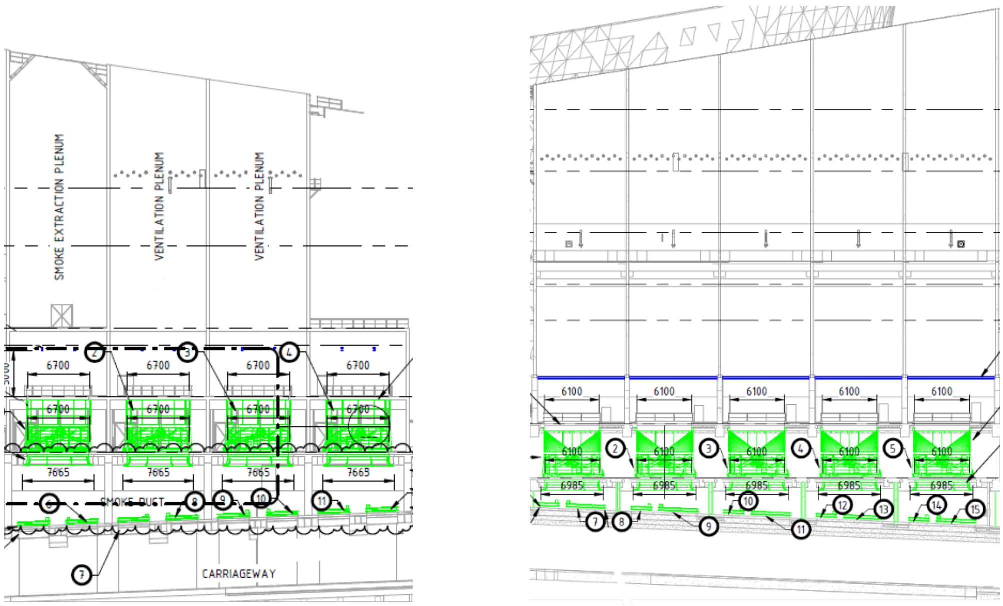
Table 1. Sound power level (dB), installed WGT fans

Fan/f(Hz)	63	125	250	500	1000	2000	4000	8000
Low-pressure	96.3	95.7	92.5	91.0	88.1	83.1	76.3	67.0
High-pressure	107.0	109.0	111.0	119.0	117.0	113.0	109.0	107.0

4 SHAFT LAYOUT AND DESIGN

Fire rated shut off dampers are located below the low-pressure fans and will maintain integrity when exposed to air at 400°C for two hours to act as a barrier between the low-pressure fans and the tunnel, allowing the fans to be mounted directly above the carriageway.

The low-pressure fan units will not be operated during fire incidents and their operational temperature rating remains at the expected tunnel temperature range of -5°C to 55°C.



(a) (b)

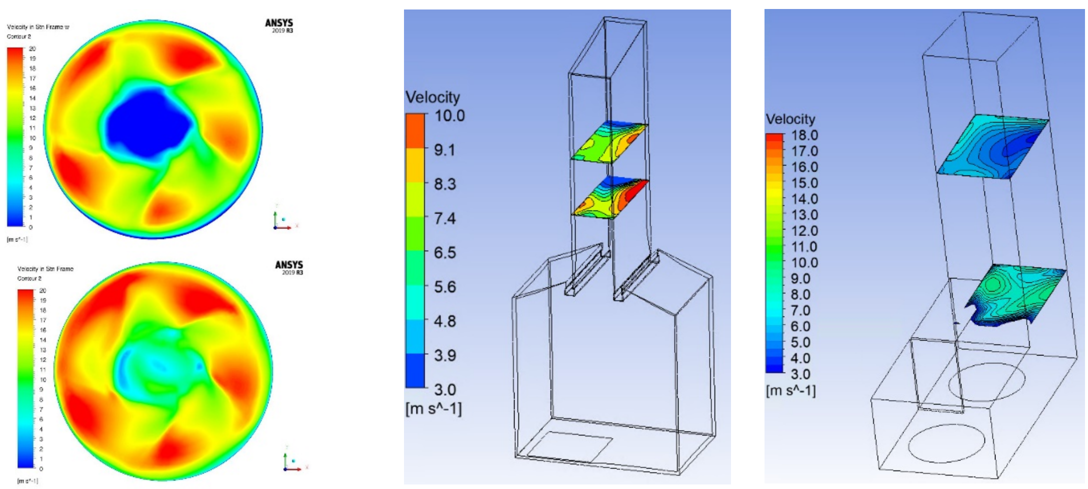
Figure 4. Portal low-pressure fan arrangements: (a) North, (b) South

At the south ventilation facility, each low-pressure fan is installed in its own vertical shaft, while at the north facility, two low-pressure fans service each of the two shafts. All low-pressure fans are mounted on movable skids for easy inspection, maintenance, removal, and reinstallation.

A support bridge holds the fan, motor, and gearbox. At the south site, low-pressure fans are installed at intermediate slab level, which opens directly out to the ground level access road, about 100m from the outbound portal. At the north site, they are positioned at ground level, approximately 100m from the inbound portal.

Tall chambers between the shut-off dampers and low-pressure fans help dissipate pressure waves from tunnel traffic, given a tunnel gradient of about 6% at the portals, the shortest chamber averages 2.5m in height. A bellmouth is installed below each fan slab penetration to reduce pressure losses and ensure uniform airflow, especially at the south portal, where the shafts are 25% offset from the fans, while at the north portal, the shafts are directly above the two central units.

Computational fluid dynamics (CFD) was performed to evaluate pressure between the low-pressure fan and atmosphere, ensuring that AS 4323.1 (1995) required airflow uniformity at the air quality measurement plane in the shaft, was met, as shown in Figure 5.



(a) (b) (c)

Figure 5. (a) Axial velocity and velocity magnitude at the fan exit; (b) South portal typical shaft velocities; (c) North portal typical shaft velocities.

5 FEEDBACK CONTROL AND MONITORING

5.1 *The control system*

The low-pressure fans are monitored with a suite of signals to screen the unit health. This includes bearing vibration (in the motor and the impeller), bearing temperature (in the motor and the impeller), motor winding temperature, gearbox casing vibration (3 axes), air volume flow and fan pressure. The signals from monitoring equipment are sent to the plant monitoring control system (PMCS) and are used by the automatic control system to activate and modulate fan speed, according to traffic and air quality in the tunnel.

During normal operations of the tunnels there are two key sub-systems at work: the first ensures that the in-tunnel air quality is at acceptable levels and the second ensures that, on average, there is always an inflow at all portals, including the exit portals. The following is a brief description of how the ventilation system works to achieve these two requirements.

5.2 *Air quality control*

Vehicles travelling through the tunnel emit various pollutants, with emission levels influenced by factors such as tunnel grade, vehicle speed, vehicle class (passenger car, light commercial vehicle, heavy goods vehicle), and engine type (diesel/petrol).

In-tunnel air quality standards mandate that pollutant concentrations remain within specified limits, both at specific points and averaged over the tunnel. To monitor these levels, groups of three air quality sensors are installed approximately every 400m, operating continuously during both normal and congested conditions.

During normal operations, when vehicles travel at high speeds, the piston effect is generally sufficient to keep pollutant levels within permissible limits, allowing the ventilation system to remain constant. However, in congested conditions with lower speeds, air quality may deteriorate, approaching regulatory limits and jet fans are activated to ventilate in the direction of traffic flow, drawing in fresh air from the tunnel entry portal to dilute pollutant concentrations. Conversely, the number of active jet fans is reduced once air quality improves.

5.3 *Zero portal emissions control*

During normal and congested tunnel operations, the project requires zero portal emissions. At the entry portal the flow is always into the tunnel due to the piston effect of entering vehicles and additional thrust by jet fans during congestion and therefore the design criterion reduces to ensuring air inflow at the exit portals. The tunnel airflow is monitored with air velocity sensors, with three sensors installed at nominally 800-metre intervals.

The key monitoring site is the last set of sensors positioned between the ventilation shaft and the exit portal, ensuring that air inflow velocity remains within the required range: if air inflow at the exit portal drops below the set range, low-pressure fans in the ventilation shaft increase exhaust airflow to boost inflow, equally, if inflow exceeds the set point, these fans reduce airflow, decreasing inflow from the exit portal.

5.4 *Control settings optimisation*

There is a balancing act between the air quality and zero portal emission sub-systems. When pollutants increase due to congested traffic, jet fans activate to ventilate in the direction of traffic, which affects exit portal inflow velocity and causes an increase in low-pressure fan exhaust.

The tunnel control system was modeled during transient scenarios to optimise set points for achieving design criteria during all operations. Key situations assessed include jet fan responsiveness during sudden congestion (when traffic slows from 80 km/h to 20 km/h in 15 minutes) and low-pressure fan responsiveness to maintain zero portal emissions during recovery (when traffic speeds up from 20 km/h to 80 km/h in 15 minutes), as shown in Figure 6.

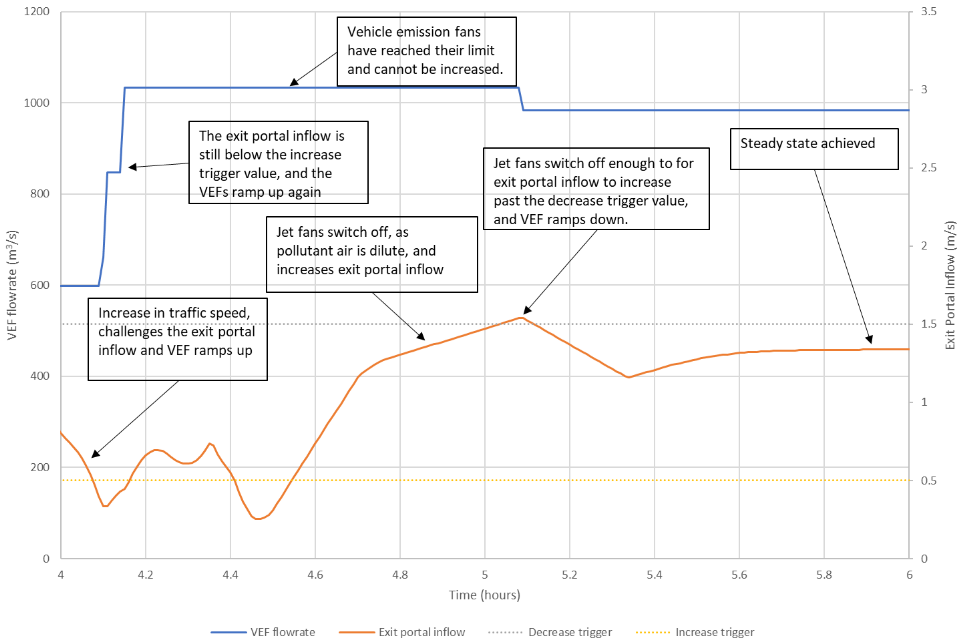


Figure 6. Control performance for morning capacity traffic transition from 20km/h to 80km/h.

6 ASSEMBLY AND INSTALLATION

The installation of large low-pressure fans requires meticulous planning and execution due to their substantial size and complexity. The fan components are procured from multiple suppliers and then assembled on-site; this approach not only facilitates tailored construction to the specific requirements of the installation site but also optimises logistical considerations by reducing transportation challenges associated with fully assembled units.

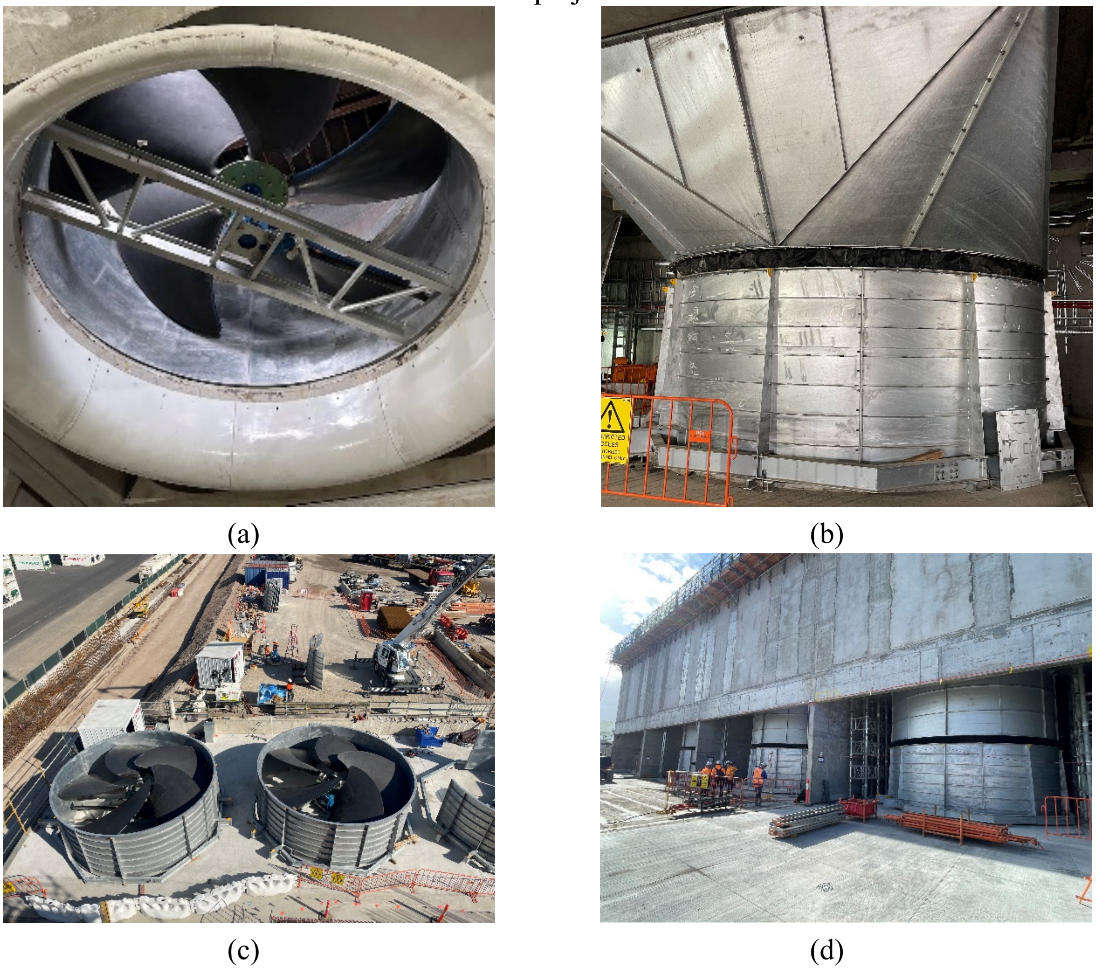
The construction, and future maintenance, takes place in a designated area adjacent to their final installed position and the pre-assembly of the low-pressure fans involves the following construction steps to ensure that every component is properly aligned and integrated:

- Base frame assembly of the steel fan base frame and partial casing assembly
- Installation of the gearbox, drive shaft, brake, motor and impeller blades
- Completion of the casing elements
- A pre-alignment of the motor, shaft and gearbox out of position
- Setting the blade pitch angle and tip gap checks for the fan

Upon completion of these pre-assembly tasks, the fan is jacked up, and caster wheels are securely mounted to facilitate easy movement. Guide rails are utilised during the relocation process, ensuring precise alignment within the allocated space while a final alignment of the motor, shaft and gearbox is completed in position. Figure 7 shows photos of various installations at the north and south portal at WGT.

7 CONCLUSIONS

This paper has detailed the characteristics of the specific WGT ventilation system, to describe what are the principles behind the low-pressure fans and how they can improve the efficiency of the tunnel ventilation system during normal operations. It also explains what other benefits are related to this system, its limitations and the controls implemented to make the system adapt to traffic and environmental conditions. Even though this specific ventilation concept might not be suitable for other tunnels due to its specific requirements (i.e. low pressure on the suction side, large footprint at the portals, no-portal emission requirement), its design principles and performance benefits should be considered on similar projects.



(a) (b) (c) (d)

Figure 7. Low-pressure fans at WGT (a) impeller and bellmouth installed in the north portal shaft; (b) South portal fan casing and transition duct; (c) Pre-assembly yard (d) North portal fan casing.

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