Fixing La Fontaine

Since commissioning in March 1967 the La Fontaine highway tunnel that links Montreal Island with the South Shore of the St Lawrence River in Montreal, Canada, has had to accommodate rapidly increasing traffic flows (now up to 130,000 vehicles a day), as well as criticism of the adequacy of its ventilation system. Plans for refurbishment to better airflow and emergency provisions are underway, and seem likely to feature a new type of jet fan reports Maurice Jones

The Lafontaine Tunnel in Montreal, or the Louis Hippolyte Lafontaine Bridge-Tunnel to give the crossing its full name after the first Canadian prime minister of Lower Canada, is an immersed tube tunnel under the St Lawrence River main shipping channel. It is made of prestressed concrete box sections carrying two main tubes with room for three lanes in each. There is also a central service tube. The tunnel's immersed length is 768m, plus connecting sections on the shores making 1,471m. This makes it the longest underwater vehicular tunnel in Canada. Its height is 7.84m, overall width 36.75m and depth down to 27.5m.

The immersed tube is set on an incline of 0.25 per cent, with the ramps at each end at inclines of 0.45 per cent.

The tunnel's ventilation is semi-transverse with twin double exhaust fan towers with diffusers at both the Longueuil South Shore end and the Montreal end. The structures also incorporate an intake for the force fans. There are 16 fans installed (eight normally for fresh air and eight for exhaust) but these are reversible. Powers range from 125hp (93.2kW) to 200hp (149kW) each.

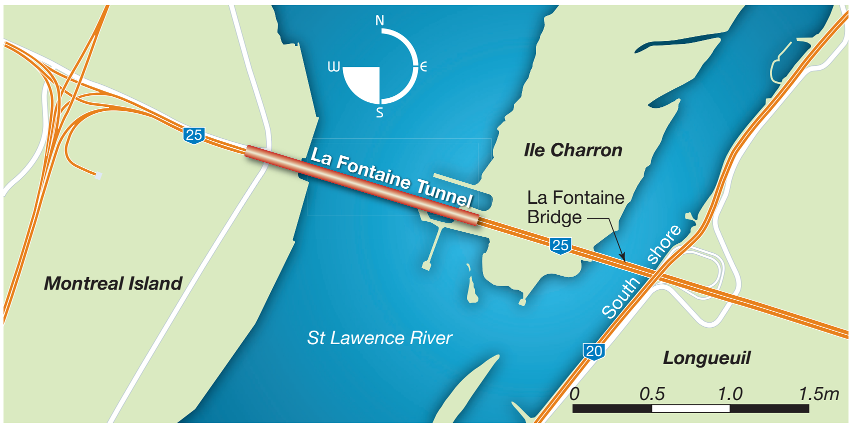
Following a tunnel fire elsewhere in Montreal in 2001, and concerns expressed by fire fighters to the Transport Quebec (MTQ) about ventilation adequacy, MTQ sought the advice of the National Research Council Canada (NRCC) to evaluate tunnel ventilation. Amongst other measures, biannual tests were conducted in the La Fontaine Tunnel overnight. Ventilation, together with electrics, lighting, surveillance and fire protection were upgraded in the early 2000s, and additional repairs were carried out in 2009. Major refurbishment including repaving is scheduled for 2014.

Top: Figure 1, typical traffic in La Fontaine Tunnel in 2009; Above: Figure 2, typical traffic in 1967

Risk analysis

Existing urban road tunnels can be narrow, leaving little space for additional ventilation equipment to upgrade the system. A study by Mosen suggests that there is a way of providing significantly more aerodynamic thrust where space is limited.

The tunnel is currently operated normally with one-way traffic is each main tube to handle vehicles at a maximum speed of 70mph (112km/h). Lanes are 12ft (3.66m) wide with a vertical clearance of 4.53m. Vehicles carrying hazardous materials are banned and other trucks are restricted to the central of the three lanes due to less



Right: **Figure 3, location of the La Fontaine Tunnel on the bed of the St Lawrence River, Montreal**

clearance on the left and right lanes.

The central service tube of twin corridors is designed for use by service employees and emergency personnel. The corridors are also used for ventilation air supply, drainage and as a refuge or evacuation in an emergency. Fresh air to the traffic tubes normally passes through frequent openings in the side of the service tube.

The general principles of the safety plan is to use the central service tube as a refuge in the event of a minor incident or fire, but also as emergency egress in the event of a major fire.

The feasibility of a tunnel safety and ventilation upgrade depends on refitting the service tube, aimed at increased user safety in the event of a major incident in the traffic tubes. In this case the design fire would be of 30MW heat-release magnitude, equivalent to a burning semi-trailer carrying non-hazardous materials. As far as location is concerned, the worst-case scenario is for the fire to be at the centre of the tunnel where air velocity is very low.

A study was commissioned by Alexandre Debs of MTQ to consider the methodology of risk analysis, as well as the particular mitigation measures required.

The methodology adopted was firstly to establish a tree of safety functional needs incorporating operational and maintenance needs and the minimum requirements of standards such as the US National Fire Protection Association NFPA 502.

Next the worst-case scenario was identified as above followed by the establishment of performance criteria for this case. There followed a brainstorming and creativity workshop to optimise the potentially 'best' solutions. Finally a value analysis was conducted to choose the optimal solution.

The tree of safety functional needs includes functions classified under regulations, safety and flexibility. Those within the overall function of ensuring safe mobility of people and goods, were:

- Ensure traffic fluidity
- Ensure traffic safety
- Protect users in incidents
- Protect the infrastructure
- Communicate with users
- Control the smoke
- Ventilate the tunnel
- Optimise maintenance
- Optimise operations
- Winter viability
- Ensure water pumping
- Ensure ice removal
- Optimise lighting
- Comply with standards

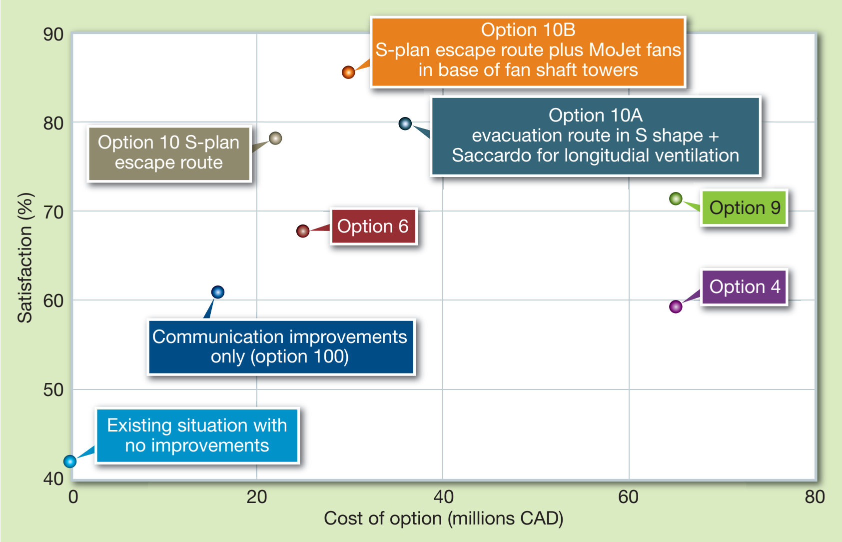
Within a performance analysis of the existing tunnel arrangements working under normal conditions, these functions were marked according to how much flexibility the tunnel operator had in meeting them (score F0 for no flexibility to F4 for more flexibility), and according to how well the conditions had been meet (out of ten).

There was very little flexibility allowed in all the functions listed, as all ratings were either F0 or F1. 'Achievement' scores range

Table 1: Performance Criteria

Weight	20.0	7.9	8.7	7.1	8.1	7.3	6.7	7.4	6.0	10.0	
Option	Safety	Comfort	Emergency egress	Constructibility	Operability	Maintainability	Technological risk	Life cycle	People evacuation	Traffic management	Overall performance (per cent)
Existing with communications improvements etc	6	7	4	10	7	1	6	7	6	7	61
Existing – no improvements	5	7	2	1	4	4	7	7	4	1	42
Option 4	10	9	6	1	1	1	6	4	7	7	59
Option 9	10	10	8	4	4	4	6	4	10	7	72
Option 6	7	7	4	8	9	7	6	8	4	7	68
Option 10	8	9	8	8	9	8	6	7	8	7	78
Option 10A	9	8	8	7	10	7	6	8	8	7	80
Option 10B	10	8	8	7	10	6	5	8	10	10	85

Right: Figure 4, graph relating cost of refurbishment solution to satisfaction/performance ratings



from as little as 3/10 for communicating with users to 7/10 for six of the listed functions. At 4/10 the functions of 'protect users in incidents', 'winter viability' and 'comply with standards' also scored lowly.

The selected worst-case scenario was inspired by a paper by Voeltzel and Dix (2004). The scenario consists of a 30MW fire in the centre of the tunnel after the collision of two semi-trailers with a stalled vehicle. The observations made, drawing on the three major tunnel fires covered in the paper, include the rapid growth of fire, making it difficult for fire fighters to reach and extinguish due to smoke and heat.

As for tunnel users, many stay in their vehicles and are asphyxiated by smoke because they lack the appropriate knowledge of how to behave in such situations. Other car drivers enter the tunnel despite red signals and it is also assessed as due to lack of appropriate knowledge.

Regarding ventilation, fresh air supply contributes to destratification of the smoke and backlayering is observed where the air velocity was practically zero.

Another performance analysis was conducted for the worst-case scenario, obviously with low flexibility in all functions. Scores for acceptability ranged from zero for 'ensure traffic fluidity' to 6/10 for control of smoke and ventilation. Traffic safety and user protection was only 2/10.

This analysis therefore identified functions to be improved including ventilation and smoke control, communications with users, user protection in case of fire, and protection of the infrastructure.

Communication measures include education of users on behaviour expected in case of fire, and real-time communication during an incident. For protection, barriers were to be considered to avoid jams of vehicles, and rapid self-evacuation was to be encouraged. For infrastructure protection automatic fire-fighting systems were to be considered as well as better fire detection.

Not all performance criteria necessary for refurbishment design are of equal importance, so weighting was applied to each (see Table 1, left).

Ventilation options

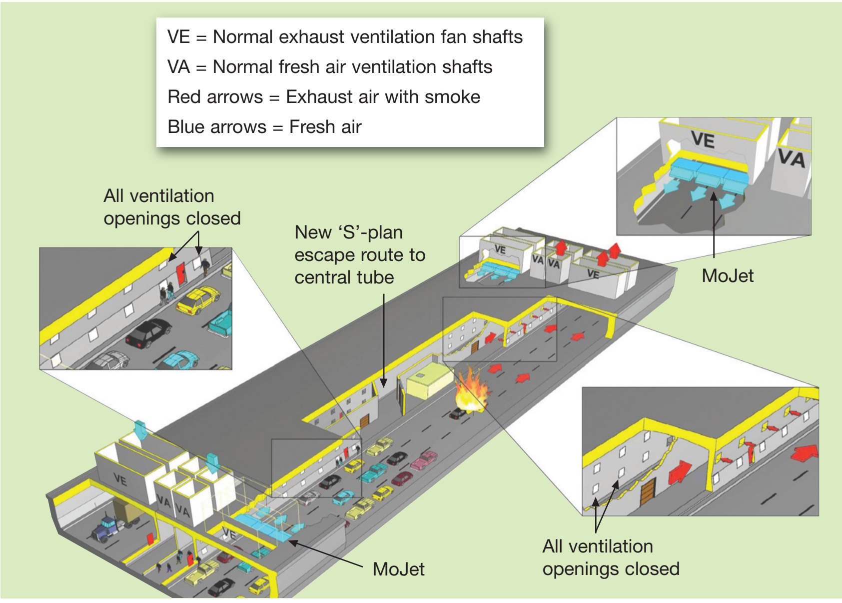
Improvements to ventilation suggested by analysis included the need to protect the evacuation route from smoke, as well as means to avoid destratification of smoke and backlayering. Following the analyses, brainstorming sessions were conducted to assess all available options for improvements to performance criteria (main results shown in Table 1). Of the options involving ventilation improvements, some required major construction works, thus reducing their 'constructability' assessment compared to other options involving little or negligible construction work.

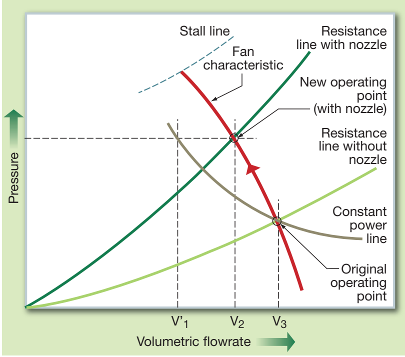
Overall the preferred option on the basis of performance was Option 10B involving the construction of an 'S'-plan escape and refuge corridor in the service tube from the centre of the tunnel, plus the installation of MoJet fans at the bottom of the existing main exhaust fan ventilation towers.

Of the other options assessed to be amongst the top performers, Option Nine involved the creation of two floors in the central service tube with a mid-tunnel division for longitudinal ventilation. This scored well for evacuation safety and comfort but low on constructability, operability, maintainability and life cycle.

Option 10 involves the 'S' escape route as with the MoJet option, but improves ventilation by the installation of more powerful exhaust fans for existing longitudinal ventilation. The upper ventilation openings near the fire are opened to allow the smoke to be extracted via the service tube at a high level, but at

Right: Figure 5, diagrammatic representation of worst case scenario using Option 10B solution including MoJets installed in base of exhaust ventilation shafts





Above: Figure 6, characteristics of a jet-fan with and without MoJet nozzle

the traffic queue all ventilation openings are closed and fresh air supplied by longitudinally through the parked traffic.

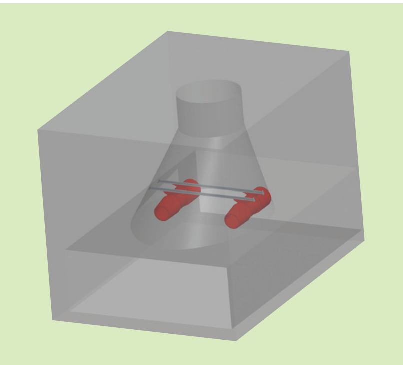
Option 10A is very similar to Option 10B but involves construction of Saccardo ducts at both ends of the tunnel to aid airflow instead of installing MoJet fans. All vents in the service tube near the fire are opened to extract smoke, but all those adjacent to the tunnel users and vehicles are closed for an escape route in fresh air.

Of course cost also has to be taken into consideration as well as performance. The cheapest, but least effective option is to simply install better communications such as better signs and signals. Other suggested measures taken include this.

Options including the construction of extra floors within the central tube, whether for longitudinal or semi-transverse ventilation, were the most expensive at an estimated CAD 65M (USD 63.9M).

Of the three Options 10, the provision of an escape route from the transport tubes to the central service tube costs CAD 22M (USD 21.6M), but on its own this scored only 78 per cent on performance. The addition of Saccardo inlets brings the estimated cost to CAD 36M (USD 35.4M). However, to use MoJet jet fans instead of Saccardo vents costs only CAD 30M (USD 29.5M) and scores 85 per cent on performance. Other forms of jet fan are not nearly as practical in the La Fontaine Tunnel due to minimal headroom, and lower aerodynamic performance. Installation of MoJets, together with installation of 'S' escape routes, is the preferred option.

Below: Figure 7, Three-dimensional design of two proposed MoJet fans within the base of a La Fontaine Tunnel ventilation shaft (Image by Systemair)



MoJet and others

Within the arguments presented by Mosen, the developers of the MoJet, it is stated that longitudinal ventilation of tunnels can be achieved by:

- Jet-fans.
- Saccardo (impulse) nozzles).
- Ventilation shafts (for example, push-pull ventilation).

Jet fans are generally preferred for shorter tunnels (up to about 3km long) since they do not require ventilation shafts and buildings. They move air in the axial direction with a discharge velocity of 30 to 40m/s. Their efficiency is influenced by the Coanda effect (eddy currents caused by interaction with tunnel surfaces and other objects), and also the installation position. The installation efficiency ranges between 0.85 for ceiling mounting and 0.73 for corner mounting. Saccardo nozzles were patented in the UK in 1898. Comprising fan inlets in the tunnel crown with a discharge angle of 30° or less, they produce a jet velocity of around 30m/s.

A version of the jet-fan is the Banana Jet, which improves installation efficiency by directing the air jet towards the tunnel centreline at an angle of seven degrees. But, according to Mosen, it produces no additional thrust beyond reduction of the Coanda effect, and also a 'wall jet' may be generated on the road surface, above which smoke can move upstream. The fan nozzles, which direct the air jets, can encroach on traffic space, depending on space available, but this is limited in the La Fontaine Tunnel and probably others requiring refurbishment.

An alternative means of improving fan installation efficiency is to use deflection louvers but these can generate a large pressure drop on the outlet sides of the fan.

MoJets are claimed to combine the advantages of jet-fans and Saccardo nozzles. They have convergent nozzles installed on one or both ends of a fan that produce an accelerated flow, and therefore an increased thrust. The nozzle is directed towards the tunnel centre-line, enhancing the installation efficiency. Mosen has applied for patent protection for the MoJet in the UK, Europe, Japan, Australia, the US, India and various Middle East countries.

The fan thrust is developed according to the equation:

$$T = \eta_i \rho A V_j (V_j - V_T) \cos\theta$$

in which:

T = aerodynamic thrust (N)
η_i = installation efficiency (-)
ρ = density (kg/m³)
A = jet-fan area (m²)
V_j = jet velocity (m/s)
V_T = tunnel velocity (m/s)
θ = jet angle (deg)

Figure 6 (above, left) shows the fan characteristic for a jet fan with and without a MoJet nozzle showing that a nozzle leads to a reduction in mass flow through the fan. The fan characteristic is preferably steep enough so that the reduction in mass flow is compensated for by increased air velocity. The enhancements in thrust are due to:

- Increase in jet velocity (typical thrust increases of 7-20 per cent are available).
- Improvement in installation (providing thrust increases of 18-37 per cent).

The overall thrust increase is multiplicative, so up to 64 per cent increase may be available. This increased thrust characteristic can be used in various ways:

- There are reduced power requirements per unit of thrust.
- Smaller diameter fans can be selected for the same installed thrust as conventional fans, so saving space.

The spatial design of a MoJet can be used to avoid encroachment into the traffic envelope, including installation positions very close to the tunnel walls and soffits. Desired ventilation effects can be achieved by MoJets installed at portals or with reduced spacing between fans, thus saving on cabling costs.

In the case of the La Fontaine Tunnel the proposal is to install MoJets within the base of the ventilation shafts so that ventilation is enhanced without encroaching on the traffic envelope (Figure 7, left)). The fans, installed in pairs, would be of 1,250mm diameter with 10-degree silencer outlet nozzles but no inlet nozzles. The fire rating of the fans is up to 250°C for two hours.