REHABILITATION OF BOSTON HARBOR TUNNEL – THE "QUARTER DUCT" SOLUTION

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ABSTRACT

Structural rehabilitation of the Sumner Tunnel under Boston Harbor will be finalised in late 2024. Associated with the structural work, the in-tunnel parts of the ventilation system had to be re-constructed. Conceived as a structural project, the base requirement was for the reconstructed ventilation to be no worse than existing. However, reconstructing the 1930s scheme carried significant schedule risk and uncertainty in the ability to achieve the Owner's Quality requirements. In addition, it would have missed an opportunity to dramatically improve the smoke management. Working within strict project constraints, an innovative reimagining of the ventilation ducts' operation improved smoke control performance using existing ventilation plant capabilities, and with only a quarter of the previous duct being rebuilt. Testing of the ventilation system before and after rehabilitation qualitatively and quantitatively demonstrated the improvements made to the smoke management. Insights from the iterative concept development, and details of the testing procedure are provided. An innovative Ventilation Test Vehicle was used to perform environmentally friendly warm smoke tests with very little demand on tunnel closure time. The ventilation concept dramatically improved fire safety, minimised change to pre-existing operations, and saved construction time, and tunnel closure time.

Keywords: Commissioning, rehabilitation, re-construction, tunnel ventilation system

1. INTRODUCTION

The Sumner Tunnel was first opened to bidirectional traffic in 1934 and currently carries unidirectional highway traffic travelling from East Boston to Boston under Boston Harbor. It's approximately 5,650 feet (1.72 km) long from portal to portal.

The tunnel configuration includes rectangular sections (box sections) of about 400 feet (122 m) in length near both portals of the tunnel, and a circular section that runs about 4,850 feet (1.48 km) in length beneath the harbour. The portal sections were constructed using cut and cover construction techniques. The circular section between them was bored/shield-driven to form a 31-foot (~9.5 m) diameter tube, using steel liner plate support with a cast in place reinforced concrete secondary lining.

Given its age and constant use, the Sumner Tunnel concrete arch, roadway deck, ceiling (exhaust duct floor), electrical, drainage, lighting, and CCTV systems needed repair and upgrading. The scope of work includes both design and construction of the reconstruction of the Sumner Tunnel. This includes the reconstruction of the roadway deck superstructure and pavement, tunnel concrete arch, and ceilings. In addition, the project is upgrading the life safety systems including lighting, fire standpipe, CCTV cameras, communications, and fire alarm systems. Reconstruction of the concrete arch and ceiling brought the in-tunnel parts of the ventilation system into the project. The benchmark on the ventilation performance was based on the existing system and the objective was to provide a solution that is equal to or better than the status quo. The base case was for the duct to be rebuilt to match the original design intent.

One of the challenges was to use the exiting ventilation plant capabilities. Changes to the surface plant, buildings, and fan plant were prohibited by the Contract. A further tremendous challenge was that the entire project, including adjustments to the in-tunnel ventilation equipment had to be constructed during limited weekend closures, and a single 80-day summer shutdown.

2. PRE-EXISTING VENTILATION SYSTEM

Figure 1 shows the long section of the existing tunnel configuration with the boundaries of the operating modes of the ventilation system. From the East Boston Portal, the tunnel goes down under Boston Harbor with an approximate downgrade of 4%, is nearly flat for a central section, and comes up on the other side with approximately the same 4% grade. There are two ventilation shafts connected to ventilation buildings approximately 300 m into the tunnel from either portal. The shafts are connected to an exhaust duct created by a false ceiling above the roadway, and separately to a supply air duct between the invert and the roadway deck. Both ducts run along the tunnel with distributed permanently open slots along the ducts, providing continuous extraction or air supply in longitudinal direction of the tunnel. The slots were adjusted, seeking to make the supply or extraction reasonably uniform over the length. A bulkhead in both ducts at the low point of the tunnel separated the ventilation of the eastern tunnel section from the western tunnel section. There are 4 supply fans and 5 exhaust fans in each ventilation building. Under normal conditions, the tunnel is operated under the lowest speed on each fan. There were three fire modes that could be activated, depending on the fire location. Those modes are mostly reused in the new scheme, minimizing change for the operations. A fire in the first 1/3 of the tunnel after the entry portal was dealt with in Mode 1, where both ventilation buildings run all exhaust fans at the maximum speed, and the supply fans are turned off and isolated. Mode 2 addresses fires in the middle third of the tunnel which is nearly flat. In Mode 2, the ventilation building on the entry end turns off the exhaust fans and runs all supply fans at maximum speed, and the ventilation building on the exit end stays in the same full exhaust function, creating a push-pull effect and moving smoke to the exit side ventilation building. The final Mode 3 has both ventilation buildings running supply fans at the maximum setting with the exhaust fans turned off and isolated. For fires in the last third of the tunnel, this effectively pushes smoke out of the exit portal.

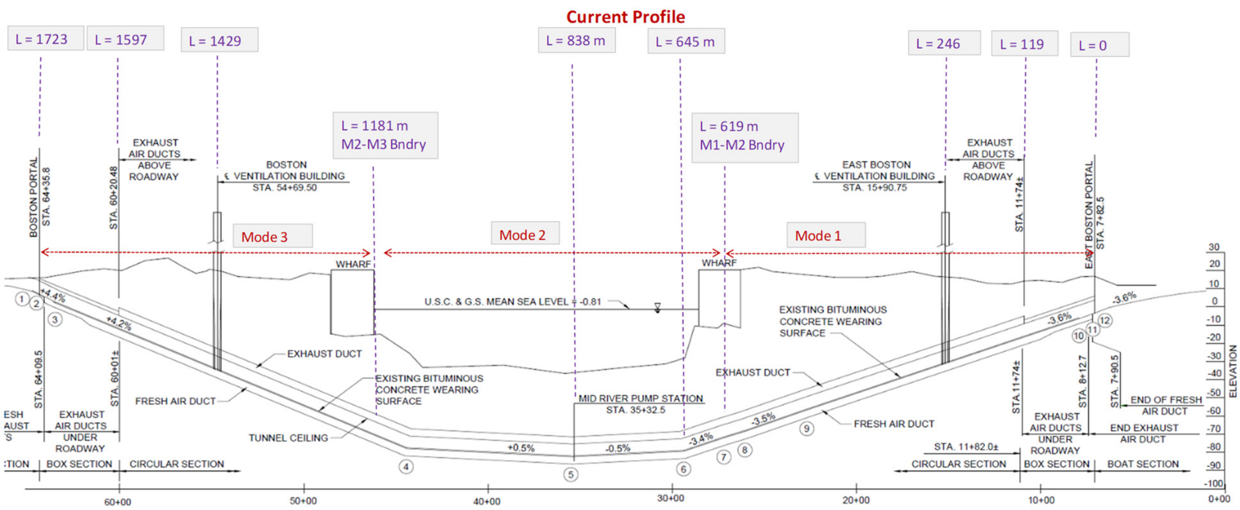

Figure 1: Long section of the pre-upgrade tunnel configuration with tunnel ventilation mode boundaries.

The existing tunnel's transverse ventilation system was originally established when the tunnel carried bi-directional traffic. However, in a unidirectional road tunnel, a primary aim of smoke control is to prevent smoke moving against the traffic direction and engulfing motorists held behind the fire. Against that aim, preliminary modeling of the system showed ventilation performed acceptably for fires occurring along most of the tunnel, but was poor on the downgrade section west of the East Boston Ventilation Building. It predicted extremely poor performance towards the bottom of the downgrade section, where the transition from Mode 1 to Mode 2 response was programmed. Mode 1, by design, has zero longitudinal flow somewhere near the tunnel midpoint, and so becomes progressively less effective as the fire location moves in that direction. On the other hand, Mode 2 (push-pull operation) is most effective for fires near the midpoint, and loses effectiveness either side of that. In the critical area near the bottom of the downgrade (around the mode transition point), Mode 1 had lost all effectiveness, while Mode 2 had not yet achieved a useful longitudinal air speed (see dashed lines in Figure 5). While that was the performance benchmark of the project's requirements, the ventilation response was not acceptable to the designers from a fire life safety responsibility perspective. So, there was a need to improve the ventilation response in the first half of the tunnel (downgrade section), all within the constraints that had not envisaged significant change.

During the final design, the Delve Stacey Agnew team performed on-site aerodynamic measurements to validate the preliminary modelling and establish the baseline performance of the existing tunnel prior to construction, but also to record the flow capacities of the ventilation buildings in different modes. These measured capacities allowed the team to refine the initial modelling to align with existing performance. That model in turn was the base for finalising elements of the ventilation concept to enhance the ventilation performance.

Figure 2 shows the achievable cold air velocities in the tunnel before the project, based on on-site measurements for the different fire modes. Figure 2 shows that the achievable velocity at the end of the planned Mode 1 zone was actually negative, pushing smoke back over the waiting traffic. Even if the Mode 1 to Mode 2 transition had been selected optimally, the achievable cold flow was only 0.5 m/s, and likely to again be negative for a hot fire.

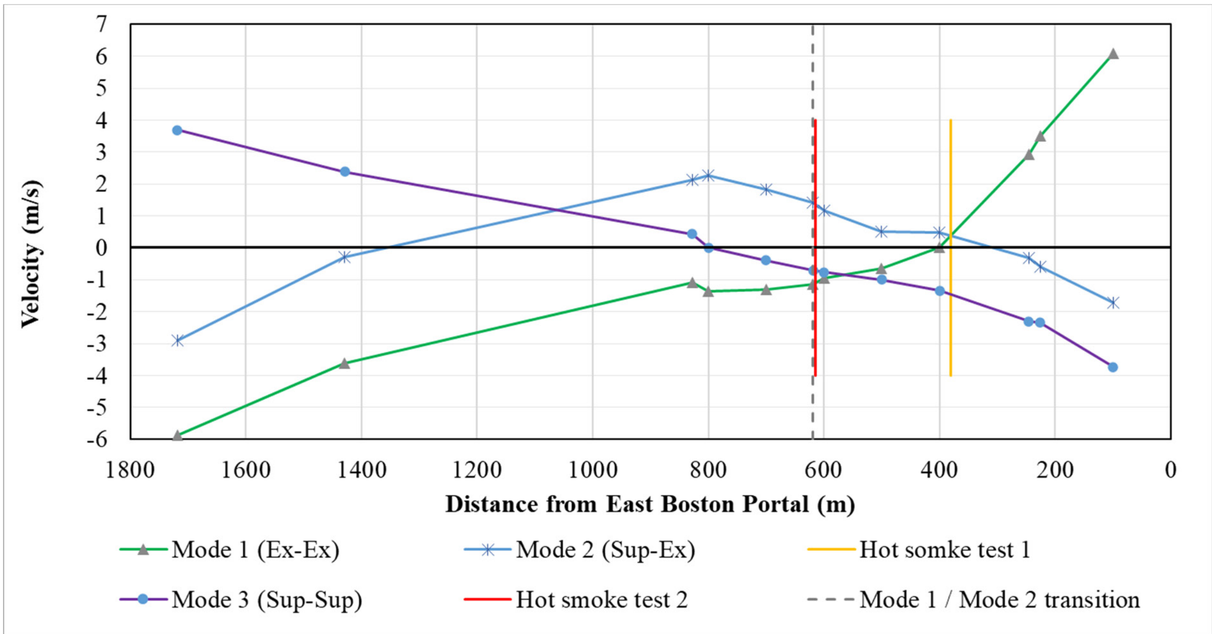

Figure 2: Achievable cold air velocities of the pre-existing ventilation system for Mode 1, 2 and 3 resulting from on-site aerodynamic measurements.

3. THE QUARTER DUCT SOLUTION

Early in the design phase, different options were on the table and discussed. Installing jet fans in the tunnel in addition to the existing ventilation plant would have been an obvious and efficient solution in terms of constructability and flexibility in the ventilation operation. Removing the false ceiling and installing 3 pairs of jet fans near each portal, in addition to providing point extraction at the bottom of the ventilation shafts, would have pushed the achievable air speed onto the fire high enough to prevent smoke backlayering at any location in the tunnel. However, jet fans were not acceptable to the tunnel owner. A further option would have been the construction of a Saccardo nozzle system at the East Boston shaft, using the existing supply fans. Calculations showed that the existing ventilation capacity (pressure) was just a bit too low to pursue that option. An entry portal Saccardo nozzle plant was also considered but was ruled out by heritage considerations.

The key to the enhanced design solution was revealed during the design team's analysis, when it was realised that a partially reinstated ceiling assisted in meeting the goal of improved smoke control, while simultaneously not changing the emissions at either portal. To do so, a new extraction point was created via the partially reinstated ceiling duct (about 25% of the previous duct length). The new extraction point is located near the bottom of the downgrade, at the 'Quarter Point' Station 27+90.75 (612 m or 2,008 ft from the entry portal). This allows extraction from both East Boston Ventilation Building (EBVB) and Boston Ventilation Building (BVB) to be applied more effectively for fires anywhere from the entry portal to the 'Quarter Point'.

In the new design, with only a quarter of the duct rebuilt, the Boston Vent Building extracts directly from the tunnel, with only a short ceiling section for maintenance and to protect the traffic from anything falling from higher in the building. The EBVB can extract from the end of the 'Quarter Duct' alone or use the Quarter Duct intake in combination with extraction directly at the base of the EBVB using a damper. Using the 'Quarter Duct' alone cannot take advantage of the maximum exhaust rate from the installed EBVB fans. The damper improves the ventilation response for fires between the entry portal and the EBVB, by using all the flow available. Use of that damper creates a new mode, called "Mode 0" to preserve the naming of the re-used modes and the numbering order. The schematic design, with the profile view and cross section of the 'Quarter Duct' is shown below in Figure 3. Figure 4 lists the fire modes for the different sections.

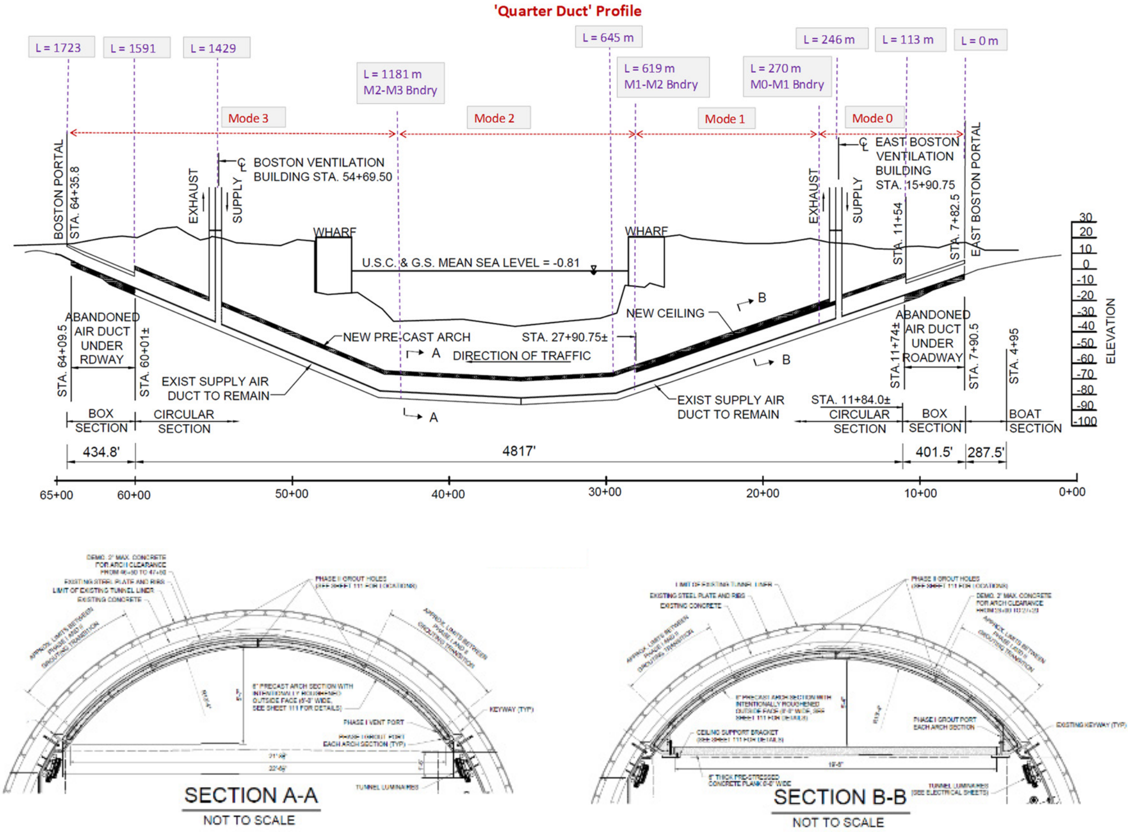

Figure 3: Quarter Duct design for Sumner Tunnel, with only approximately 1,200 feet of the ceiling reinstated. Long section shows the mode boundaries and the extent of the new ceiling, with the detail of the profile shown in the cross sections.

Mode	BVB	EBVB	EBVB Damper
Mode 0	Emergency	Emergency	OPEN
Mode 1	Emergency	Emergency	CLOSED
Mode 2	Emergency	Pressurize	CLOSED
Mode 3	Pressurize	Pressurize	CLOSED

Figure 4: Fire modes with 'emergency' (exhaust fans at maximum speed) and 'pressurise' (supply fans at maximum speed) operations at each shaft.

While Figure 2 showed the measured cold flows achievable, the flow that is really sought is the flow onto the 30 MW design fire, including the buoyancy effects. That is assessed by 1D simulation using the model calibrated for the cold flow measurements. Figure 5 shows the predicted achievable air velocity onto a 30 MW fire for different fire locations in the tunnel. The dashed lines are predictions for the ventilation system as it was performing prior to the upgrade, and the solid lines are after the upgrade.

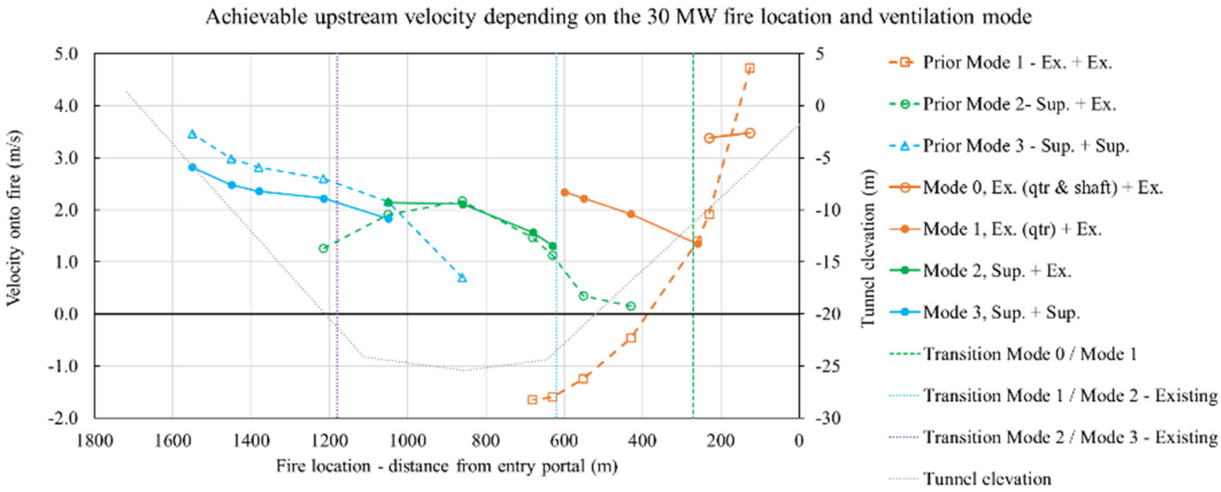

Figure 5: Modelled achievable upstream velocity throughout tunnel with a 30 MW fire in Modes 1, 2, and 3 for the existing system and in fire Modes 0, 1, 2 and 3 for the 'Quarter Duct' design.

The improvement in the performance for the region between 280 m into the tunnel and the end of the 'Quarter Duct' (600 m in) is dramatic. Previously the velocity onto the fire was less than 0.3 m/s for a significant section of the tunnel. That is a result from a 1D model. Acknowledging the 3-dimensional reality of a 30 MW fire, velocities that low, at 4% downgrade, would result in rapid uncontrolled backlayering, and engulfment in smoke of people uphill of the fire.

With the Quarter Duct solution, modelled achievable velocities in that section of tunnel are generally around 2 m/s, with the lowest being 1.4 m/s. While that is still not meeting critical velocity, it is a dramatic improvement. It would likely manage smoke for the early stages of a fire, permitting evacuation back upgrade.

4. MEASURED RESULTS

Two test sessions at the completion of construction changes to the ventilation system showed the end result. Of course, the air speeds are recorded without the 30 MW design fire, but they can be compared against the same cold flow records from before the upgrade. That is done in Figure 6. The dramatic improvement in the downgrade section between the East Boston Ventilation Building (246 m) and the end of the Quarter Duct (612 m) is clear from the plot.

The 'Quarter Duct' scheme not only addressed the very poor ventilation performance between roughly 250 m and 600 m into the tunnel, it also allowed increased extraction flowrates at the Boston Ventilation Building by eliminating all the exhaust duct in the western end of the tunnel. This would also have assisted the result in the mid-section of the tunnel (610 m to 1180 m) where Mode 2 applies. As Mode 3 only involves the supply system, which was not upgraded, no significant change was expected in the air speeds achieved in the western third of the tunnel. Further, by removing the ceiling in the three quarters of the tunnel (from approximately 600 m into the tunnel up to the box section at the Boston Portal (except for the very short section at the bottom of the BVB shaft) an additional smoke reservoir was created, still keeping the air speed in that section almost the same. During the Mode 0 test, only four of the five EBVB fans ran. The intention was that all five would run, but that doesn't seem necessary.

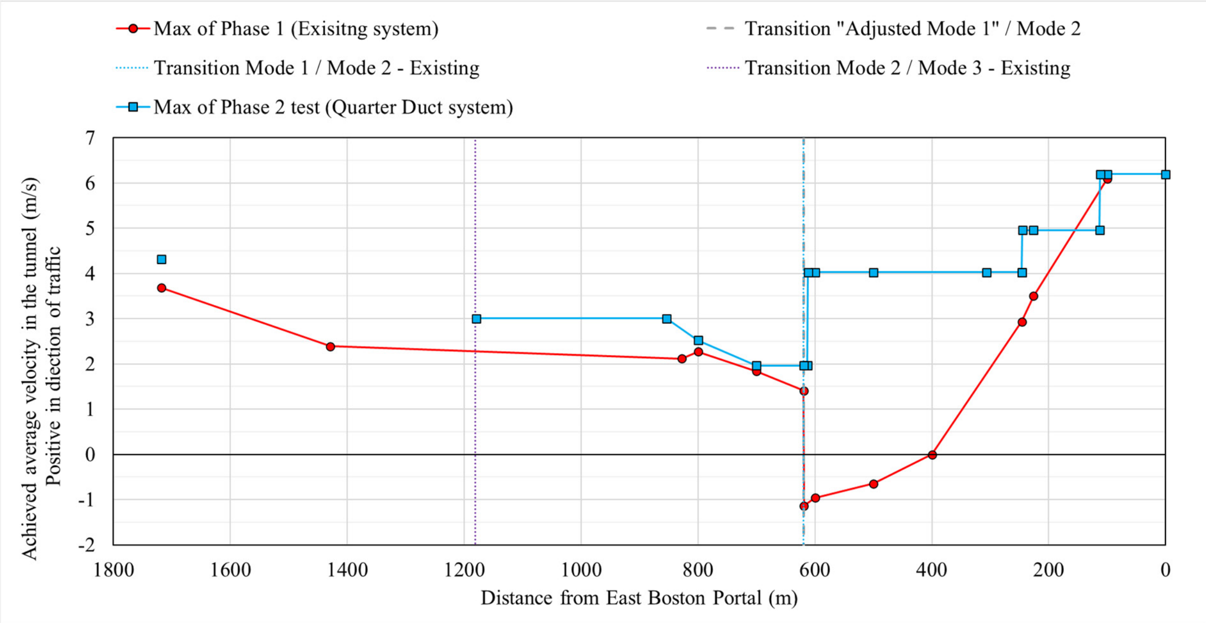

Figure 6: Achieved 'cold flow' velocities in the tunnel for the programmed emergency modes. Red line depicts the results of the ventilation system obtained during pre-upgrade testing, and the blue line depicts final results with the Quarter Duct system fully commissioned.

5. WARM SMOKE TESTS

You can wave anemometers till the cows come home, and publish the most carefully analysed models of ventilation response, but for achieving a common (whole project team) clarity of understanding about what is going on in the different modes, there is nothing quite like watching buoyant smoke in the tunnel itself. Delve Stacey Agnew's Ventilation Test Vehicle (aka Smoke Bus) was mobilised for both the before and after tests, with some images given below. The Smoke Bus was driven into position and a large quantity of harmless buoyant 'smoke' could be created within minutes. When the programmed ventilation response is implemented, and the smoke goes backwards, the need becomes clear. Besides creating a video record of the smoke behaviour, the use of the Smoke Bus facilitated the discussions around the ventilation performance.

Figure 7: Images of the Delve Stacey Agnew Smoke Bus at various stages of different tests, producing copious quantities of hot 'smoke' in service of demonstrating visually the ventilation system performance.

6. COMMENTARY AND CONCLUSION

The testing results, and the hot smoke tests, showed that the ventilation response, and therefore the smoke management during a tunnel fire, was significantly improved by the project. It is noted also that the cross section of the tunnel is larger without a smoke duct, giving more room for any layering smoke in the arched tunnel obvert. Even if the velocities had stayed the same, the larger, taller smoke reservoir would improve the chances of successful egress in a fire, from those areas in which the duct was not rebuilt.

Referring to Figure 6, there is a similar air speed in the western (upgrade) section, and a slightly improved air speed in the 'flat' (mid-tunnel) section. The problem before the project was with the flow in the downgrade section. The achievable "cold flow" velocity in the problematic downgrade section is dramatically higher with the Quarter Duct system using the existing fans.

At the outset, the project had not envisaged upgrading the ventilation, so there was not time or cost allowance for doing so. There were also significant constraints, both physically and organisationally. The unacceptability of jet fans, and the impossibility of Saccardo nozzles eliminated those two obvious options, and so greater creativity was called for. The Quarter Duct design was a very successful innovation generated within the project, achieving improved ventilation results with greatly simplified re-construction (replacement of only a quarter of the previous duct), which enabled the project to be completed within the time allowed by the Contract and the budget established at Tender, while giving the tunnel owner a dramatic improvement they had not asked for in the documents.