Commentary on tunnel ventilation system design with respect to tunnel rehabilitation

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ABSTRACT
There is a concerted ongoing effort to expand infrastructure and extend the useful life of systems. The rehabilitation or repurposing of existing tunnels is expected to be a common occurrence in upcoming projects. One critical system for the success and safety of these projects is the tunnel ventilation system (TVS), which must support tunnel fire life safety and achieve the requirements of codes and standards. Therefore, the TVS must be designed to address several specific challenges when working within existing tunnels.

Tunnel users, responding emergency services, and maintenance and operations staff require systems that protect in the event of a fire and maintain air quality during operations or maintenance. Expanding service or modifying systems can challenge the infrastructure by introducing more frequent or higher volumes of traffic and higher loads that cause a greater strain on normal operations ventilation for air quality and user comfort. New rolling stock, mixed fleets, or increased traffic could require systems to be sized for large or extreme fire events. Furthermore, engineers often face poorly documented or aging systems that must be repaired, repurposed, or replaced. Addressing requirements for increased performance within existing geometric constraints and respecting the original structures requires creativity and forethought. Aging existing systems may also face reliability or service challenges that could require engineering within a system designed for outdated standards. This paper provides commentary on experiences designing for such challenges and recommendations for addressing.

1 INTRODUCTION

Tunnel ventilation systems (TVS) are installed in tunnels and stations to provide ventilation during normal operations, special normal scenarios, and fire incidents. This paper focuses specifically on tunnel ventilation in transit train tunnels, but the principles also apply to other tunnel uses. A TVS is designed and installed per applicable legislation and standards, particularly NFPA 130 - Standard for Fixed Guideway Transit and Passenger Rail Systems in North America, building codes, and health and safety codes. These codes and standards provide requirements and criteria to design and assess the ventilation system.

Ventilation in normal conditions focuses on the comfort of tunnel users: specifically aural comfort from train induced pressures, fresh-air delivery, and air temperatures. Special normal scenarios consider maintenance activities and congested operations. During maintenance pollution generated from equipment and activities must be managed. In congested operations, where a train has stopped within the tunnel, a fresh air supply is required for passenger comfort and to maintain operational temperature requirements.

Per NFPA 130, tunnels longer than 305 m require a mechanical ventilation system. The system must be supported by engineering analysis with a validated subway analytical program or computational fluid dynamics
modelling. Tunnels longer than 61 m may require a mechanical ventilation system, determined by an engineering analysis. Tunnels less than 61 m do not require mechanical ventilation per this standard.

TVS capacity is driven mostly by the fire incident response, which requires large volumes of fresh air to protect egressing passengers and control smoke spread. The design fire heat release rate and tunnel geometry are the main factors in this analysis. The fire response is to supply fresh air and exhaust smoke in sufficient volumes to provide a tenable path of egress. In tunnels, operation of the ventilation system directs smoke one direction, in the opposite direction of passengers’ egress. Complete control of the smoke (no backlayering of smoke in the egress direction) occurs when the critical air velocity is achieved. In stations, the fresh air is drawing through the entrances and station public spaces, exhausting smoke into the tunnels or ventilation shafts, allowing passengers to safely evacuate through the station.

The TVS is designed in a coordinated effort considering other services, structural, and architectural requirements. The requirements of the emergency personnel, authority having jurisdiction, and client also must factor in.

Beyond this, when working with existing tunnel infrastructure additional challenges arise. This paper outlines several experiences on past and on-going projects, finding and addressing challenges with existing tunnels being updated for new levels of service or line expansions. Each tunnel described was originally constructed and put into use before the 21st century. Constraints can mean that achieving complete code compliance with today’s regulations is challenged, but each project features efforts to achieve compliance and reduce fire life safety risks.

2 DISCUSSION

The overarching principal for general fire and life safety systems is to mitigate hazards to an acceptable level of risk. Code compliance is the most common way of demonstrating that acceptable practices have been followed and risk mitigation achieved to the appropriate level. Detailed reports, drawings, and analysis, reviewed in concert with owners and emergency responders, also demonstrate the level of safety. Operational plans also play a role in this.

For the longevity of systems, ongoing maintenance and repairs are required. Even with this, systems may begin to experience issues at or beyond their design life. As operational requirements change, systems too may need an update.

Working with existing systems provides an additional challenge as documentation on existing designs and analysis is often missing or incomplete.

Below, experiences from four projects are described. Project A is the upgrade of an existing diesel light rail transit tunnel. Project B is the modernization of a legacy system for which the level of service is also being increased. Project C features a few tunnels along a light rail transit (LRT) line that are beyond their service life. Project D connected a new transit line to existing tunnels.

2.1 Project A: Diesel Light Rail Transit Tunnel

Project A is the extension of an existing transit line. Engaged on this lump-sum turnkey design-build-finance-maintain project, the scope was to upgrade and update an existing tunnel for use in the extended transit system from design through construction. The existing transit line began service in the early 2000s and used diesel multiple unit (DMU) powered light rail vehicles and had five stations while the new line will add an additional eight stations and connection to the city’s airport. The extension will continue to operate the existing light rail vehicles, but also expand the fleet with new DMU vehicles.

Built along a disaffected freight corridor, the alignment was originally constructed in the 1960s for freight traffic only and included a ~600 m long cut and cover tunnel. The tunnel has a rectangular cross-section and features a gravel trackbed with wooden ties, lighting, and walkway along one wall connecting three safety bays. The
bays provide some refuge along the tunnel (likely for maintenance staff to shelter from freight vehicles) and at the center safety bay there was also a sump pit which connected to a pumphouse at grade. The pump management, backup generator, control systems, and TVS were housed within this pumphouse.

While a portion of the original alignment was taken over for transit use, the provision remains to allow infrequent freight traffic outside of revenue service periods. This freight traffic provision must remain to ensure the original owner of the guideway maintains their use of the alignment. The future electrification of the system would preclude freight use, but no concrete plans are in place for this at the current time. Space provisions must also be provided to allow for this future electrification.

The tunnel has included a ventilation system since it was built, but no documentation of the design or construction of this system was available. Based on inspection of the system, it is assumed it had not been modified and was sized to flush pollutants from the tunnel during freight traffic use only and was not sized for fire emergency response. When the guideway was modified and put into use for the light transit system, no modifications were made to the ventilation system. Project A will upgrade and update the tunnel’s systems for modern code compliance.

Only limited documentation was available on the original construction of the system. The fire incident response of the tunnel ventilation system was investigated when transit use began, but this too lacked detail. At the outset of the project, the system was still active, but the performance was unknown. A key challenge from this was that the existing TVS investigation report provided an analysis of the fire response that did not demonstrate modern code compliance. This report also did not detail the determination of the fire size used and was for rolling stock that is no longer in service. This report provided a smoke stratification assessment that demonstrated smoke would remain above the height required for emergency egress, but this would not be considered acceptable per NFPA 130 today as critical velocity was not achieved in the reported modelling.

To address this, the system had to be replaced and upgrade to provide additional air flow. In the process of upgrading the TVS, other shortcomings could also be rectified: equipment temperature rating, power supply redundancy, and single point of failure resiliency, among others. The rolling stock also had to be assessed to determine an appropriate heat release rate fire size to dictate the design.

A key challenge of the system was the space proofing of the new TVS and other systems. The project specifically did not allow for the modification of the tunnel structure to preserve the integrity of the tunnel. Maintaining a freight vehicle clearance envelope and space provisions for future electrification, specifically an overhead catenary system (OCS), were also required. These constrains only provided limited space within the tunnel to install new systems, along the walls or in the upper corners. To help address this challenge detailed modelling of the entire tunnel was required to allow for clash detection. Initially, Project A started with a model of the tunnel and pumphouse created from the 1960s as-built drawings, but it was quickly found that this lacked the necessary level of detail. The tunnel structure was then modelled based on 3D laser scans of the structure and each new and existing component was then incorporated. Converting the laser scanned point cloud into a useable model posed challenges given the size of the dataset for the length of the tunnel. To address this the data was somewhat simplified into distinct polygons. These rectangular elements were made to approximate the dimensions for the various tunnel sections, but where then adjusted to fit the point cloud. This created a useable model, but reduced its accuracy, so some additional clearance had to be assumed in the clash detection if tight tolerances were required. Clash detection could then be used to find and resolve conflicts. Figure 1 below shows the tunnel cross-section along with wall mounted infrastructure and the various required clearance envelopes (freight and LRT vehicles, OCS and pantograph, and emergency walkway). The TVS jet fans are shown in the upper corners of this section.

Upon initial site investigation it was noted that the ballast depth was below standard. Under the ties the gravel was reduced to a fine powder, having been crushed against the tunnel structure. Increasing the ballast to the appropriate depth, which should prevent this excessive wear, required the reduction of the freight envelope slightly to prevent conflicts with the tunnel. The minimum reduction possible was done to not preclude freight use and accept the required systems. This had to be agreed with the client.
To accommodate both transit and freight clearances, the emergency walkway had to remain down at track level, which would require egressing passengers to first get down from the height of the train floor to track level. No other option was available due to the space limitations, but this would be a concern for passengers with reduced mobility. Considering the other improvements, the safety of the system will be improved holistically relative to the current operations. Passengers and any available staff would have to assist each other with egress onto the walkway. Ideally, the walkway would be continuous at the floor level of the train.

The limited space also forced the TVS fans to be installed in a highly inefficient installation, with practically no space between the fans and the walls and ceiling in the upper corners of the tunnel. This installation causes high losses due to air friction with the wall and ceiling and prevents the fan from drawing in air from all sides. Nominal installations allow for at least one fan diameter between the fan and any adjacent walls, but here only less than 200 millimeters would be available, a quarter of the diameter. To combat the increased losses and low efficiency, deflector vanes were specified at the ends of the fans. Past project experience showed this would increase the jet fan efficiency from as low as 25% to more than 60%. Nominal installations are usually assumed to be 80% efficient, so this is still a decrease in efficiency from typical that requires increased total fan thrust.

In the updated assessment of the fire heat release rate, both new and existing vehicles had to be considered as they would both operate through the tunnel. The supplier of the new vehicles was able to provide most of the information needed and even with a conservative assessment method, the resulting fire size was very similar to what had been used in the legacy report. The existing vehicles, however, did not have the same level of information available, nor were they built to the same standard – not being specified for underground use. For this, conservative assumptions had to be made regarding the performance of the materials and potential extent of the fire spread. A heat release test was done on a sample of the seat material, as this is a critical input into the analysis and an incorrect assumption would drastically impact the result. Through this analysis, the design fire size came out approximately 25% higher than that used in the legacy report. To achieve the project schedule, both the TVS design and fire size analysis were occurring simultaneously, so this change resulted in further studies and changes to the TVS design. Close engagement between the fire hazard engineering team, TVS team, and equipment suppliers, was critical to achieve the increased performance requirements. The thrust of the fans was able to be increased without changing the exterior size, which provided enough thrust to control this heightened fire size.
2.2 Project B: Tunnel Modernization

Project B is the construction of a new fully automated rapid LRT line connecting across a major city using an Engineering, Procurement, Construction project model. The project is divided into branches, two of which have underground sections. The branch to the airport will have a newly built tunnel and station (outside the scope of this paper) while the city center branch adds two underground platforms on an existing 5 km long tunnel. The existing tunnel will be modernized and brought up to current code compliance. Here the new transit line will repurpose and assume full use of the existing tunnel. Figure 2 below shows a sketch of the tunnel alignment and sections.

This tunnel previously served commuter rail services. Originally, it featured a single mid-tunnel ventilation shaft and no stations within the tunnel. The ventilation system appeared to only be sized for normal operations, providing fresh air and pollution control for less frequent commuter traffic. Only electric vehicles have been used in the tunnel, and that remains the case with the new system. Had the tunnel originally been used for diesel traffic, the ventilation system would have been larger to handle the higher pollution loads. In the new system, two station platforms are being constructed within the tunnel. These platforms will be separated from the tunnel with full-height platform screen doors. This will help separate the two spaces and improve the safety of the platform. In addition to keeping passengers off the tracks, the doors will also decrease the amount of smoke entering the platform during tunnel or station train fires and reduce the ventilation requirements of the stations. Overall, to meet the requirements of the new system, a complete redesign of the ventilation system has been done, including the construction of new ventilation shafts, some up to 60 m long, and the addition of in-tunnel jet fans. A particularly interesting solution to the TVS design was that the original twin-track tunnel will be modified to include a fire rated dividing wall, separating the two tracks. This greatly improves safety and tunnel ventilation performance. As the TVS must only ventilate a tunnel fire within the smaller cross-sectional area, the ventilation load is reduced. The non-incident tunnel would also then be available for egress through cross-passages, helping separate passengers from the fire more quickly.

Separate bounds help improve the air exchange caused by the normal motion of the vehicles. In a twin-track tunnel, the air motion induced by passing trains tends to cancel out and reduce the overall air exchange between the tunnel and atmosphere, resulting in higher tunnel air temperatures and lower air quality. With the dividing wall and platform screen doors, the induced airflow is directed through the ventilation shafts regularly and predictably.

Figure 2. Project B existing tunnel alignment and section views.
2.3 Project C: Expanding LRT Service

Project C supported the owner and operator in assessing an existing transit line to develop roadmaps for the future rehabilitation of the TVSs of the line’s three tunnels. This line was constructed in multiple phases, so three TVSs were built for three separate underground sections at different times. The oldest two systems were from the 1980s and remain mostly original, generally only modified as required for maintenance. The final TVS was build much more recently in the early 2000s. The level of available documentation for this line was useful, with the most recent system being very well documented.

The specific challenge with this system was that the older ventilation systems had exceeded their design life. Maintenance and a few small equipment replacements had been done and the system continues to operate today. With new, larger, vehicles coming into service and equipment age starting to become an issue (replacement parts becoming unavailable), the operator has started to investigate replacing or rehabilitating the equipment and systems. Completing such a scope of work while maintaining service to the growing number of users is a critical challenge that cannot easily be resolved. Breaking work activities into short sprints can help reduce the need for lengthy system closures but maintaining capacity throughout construction would likely not always be possible. Completing projects jointly, such as station renovations including equipment replacement, would be ideal to limit customer impacts.

The beginning of this rehabilitation program was a thorough condition assessment and code compliance investigation. The code compliance was assessed against both the code applicable at commissioning and the most recent versions. While there were some shortcomings relative to the modern codes, the systems were compliant relative to its original code.

The conditions assessment revealed a few key issues requiring urgent attention. One issue was a broken fan housing flexible connector that allowed air to leak out of the TVS. This small break in the fan ducting caused measurable reduction in airflow within the tunnels and was sufficient to limit the whole TVS’s performance. While an important issue, the part was easily replaced. This highlights the importance of regular equipment testing and inspection to ensure effective operations. Another issue observed impacting the operations of another TVS was a sensor had been disconnected at some point during maintenance activities, but there was no information on why or when this had been done. The sensor was used to detect if a fan was not operating, with the intent of then closing a damper to isolate the trouble fan. Trying to reconnect the sensor did not solve the issue and testing of the TVS showed that failing to isolate a trouble fan would reduce the provided airflow greatly due to air recirculation within the ventilation shaft. This was able to be resolved as the whole control system was replaced to remove and update the original controller for which replacement parts were no longer available. The system continued to operate with the temporary sensor disconnect prior to the control system replacement as modelling was done to assess the impact of a potential fan failure scenario. This modelling was able to show acceptable results. It is also worth noting that the system remained compliant to the original code with this issue. Another TVS control system had also been modified so that the system could only run in one direction (exhaust to the tunnel portal). Although fire response would practically only use this ventilation direction, being able to operate in both directions is important for emergency egress and fire fighter response. This issue was highlighted as a fix to be implemented for the future system rehabilitation as the main fire response remained fully functional.

Following the condition assessment and code compliance review, the systems were modelled, and the performance was evaluated with respect to fire incident and normal operations. The impact of new rolling stock and several proposed station modifications was also investigated. Site testing and airflow measurements were done to ensure the models accurately reflected the TVS operation. This ensured that the model reflected the current performance of the system and was then able to demonstrate that the increased levels of service would maintain normal operations comfort levels and maintain the level of code compliance in fire emergency response. Using field measurements to validate modelling is a critical step when working with existing systems, especially when the equipment performance is uncertain.

One station modification that was investigated thoroughly was the extension of a tunnel to support a future residential development. The objective of the analysis was to determine what work was required to maintain the TVS performance with the increased resistance of a longer tunnel. The study showed that the TVS
equipment had to be upgraded to maintain performance with the increased tunnel length – something that the developer supported to ensure their project could go ahead. The TVS upgrade was designed such that the code compliance could be maintained without having to bring the whole system up to modern requirements. While ideally the system would have been fully revamped, this would not have been possible at that time so it was determined that the extension and equipment replacement could go ahead as at least the original performance level was achieved. Critically, the upgrade was accomplished by replacing the existing TVS fans with new, higher performance models, but without any further modifications to the station, operations, or use. Here too clash detection was critical, with the fans placed right up against the limits of the train clearance envelope.

2.4 Project D: Connecting New and Existing Transit Tunnels

Project D is constructing a new LRT through a major city with both at-grade and underground stations and guideway. This is the first phase of a large transit development across a section of a city. In addition to a tunneled section with underground stations, there are also standalone underground stations. Specific challenges related to existing tunnels occur in this project at the underground interchange stations, interfacing with existing systems. Another challenge with the project was ensuring the design protected for the future extension from a partially underground terminus station.

The interchange stations connected new and existing systems. At one of interchange station (Station A), new and existing ventilation systems were aerodynamically connected through the station public spaces. A sketch of this is shown in Figure 3. The existing system was a part of legacy transit line not up to the latest codes and standards. Further site investigations showed that the existing system may not perform as it was originally designed with mechanical flaws visible. For example, dampers with missing blades were observed. To validate the design analysis done and additional site visits were planned to assess the achieved TVS performance of the existing system, which would then be used to calibrate the model for the new combined station. The general objective of the design and analysis was to show that the addition of the new station either maintained or improved the performance of the existing system. This was accomplished by ensuring the new TVS capacity could support fires in either the existing or new station sections. Similarly, a second interchange station (Station B) connected to an existing underground station and tunnel (this time with a natural, non-mechanical, ventilation scheme). This was modelled in both pre-construction and post-construction configurations, demonstrating that the addition of the interchange did not negatively impact the ventilation performance of the existing areas. For Station B, fire rated doors were used to aerodynamically separate the stations at the underground connection, which was on the concourse level.

Figure 3. Project D interchange Station A section showing the new station areas and existing station platform

The design and construction of the partially underground terminus station was required to allow for the future extension of the line and continuation of the underground guideway. The partially underground form of this station means that it was able to incorporate many openings to atmosphere along the platform and through the station entrances. With the short entrance tunnel, with many openings, and space constraints within the other areas, the station could not use a typical ventilation design scheme. The entrance tunnel side of the
station had no mechanical ventilation system. Beyond the platform (after the end of the transit line), the design utilized fans installed within the tail track tunnel. Placing the fans within the tunnel reduced the overall station size and considerable civil work due and was done due to concerns with limited real-estate available for fans. This scheme, however, placed the fans in the way of the future extension of the tunnel. With all constrains in place, the path forward was to strategize how the extension of the line could make the best use of existing system with minimum potential impact, proposing the installation of two axial fans and shafts beyond the end of the tail track, and relocating the currently installed fans as jet fans near the portal of the future tunnel extension. Thorough modelling was able to demonstrate that both the current and future TVS design were acceptable, and this was able to prove that the terminus could be extended.

3 CONCLUSION

This paper provides commentary on the author’s experience with tunnel ventilation system design and construction within existing tunnels and stations from a selection of project examples. From these experiences, ensuring close coordination between all disciplines is clearly important. Space proofing, system integration, and support to address challenges are all much easier in a well-coordinated team. Furthermore, it is of upmost importance that the engineers work closely with the operators, owners, and emergency responders to ensure project success.

When working with an existing structure, thorough site investigations and system inspections are critical. Testing, especially airflow measurements to calibrate modelling, greatly improves confidence and ensures requirements are met. Space proofing is always a challenge when working with existing systems and the use of 3D modelling and laser scanning were highly effective for working with the constraints.

It is not always possible to update systems to achieve complete code compliance with modern requirements, but the principal objective should always be to make risk and hazards as low as reasonably practical. If it is not possible to meet some requirements, it is recommended to work to address these issues through other means. An upgrade is generally an improvement from current conditions so working towards modern code compliance, even with limitations, is a step in the right direction.

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