ABSTRACT

Ventilation systems form an integral part of the fire-life safety systems for underground rail or metro systems. For older systems there is a need to assess the condition of equipment and assess options for rehabilitating or upgrading performance to try and meet modern present day standards. This paper outlines a comprehensive approach to rail system ventilation rehabilitation considering fire potential, ventilation performance, and overall fire-life safety risk.

KEYWORD: rehabilitation, design fire, CFD, ventilation, rail, metro, risk

INTRODUCTION

Ventilation systems form an integral part of the fire-life safety (FLS) features in underground rail and metro systems. As these facilities age there is a need to rehabilitate the fans and associated equipment. Many of the world’s rail and metro networks predate modern FLS design standards such as NFPA 130 [1]. Although most standards have “grandfather” clauses for FLS, it is good practice to not only rehabilitate the ventilation system, but where possible to upgrade the performance.

The first goal of a ventilation rehabilitation project is typically to bring the system to a state of good repair. Older systems were not typically designed with the same level of FLS analysis, such as computational fluid dynamics (CFD) modelling and egress analysis, as modern systems. Rolling stock fire characteristics may also have been based on limited information at the original design phase. These considerations mean that bringing an existing system to a state of good repair may or may not result in better FLS outcomes. It is therefore helpful to characterize the system’s current performance as part of a rehabilitation project. This paper covers a three-step approach to rehabilitating a metro ventilation system that combines railcar fire testing and simulation, CFD and egress analysis, and risk analysis. This approach is already being applied to an existing metro system in the United States, where NFPA 130 is the applicable design standard.

BACKGROUND

In order to better understand the need for rehabilitation some background material is presented, considering three main themes: previous underground rail fire incidents, current US experience with rehabilitation projects, design fire development, and risk assessment and acceptance.

Underground Rail Incidents

A thorough review of previous rail fire incidents (metro and heavy rail) is provided in literature dedicated to the subject [2]. This review helps to understand the societal need for FLS features in an underground rail facility. From that literature there is an emerging theme to the nature of fire incidents, which is that the most common fire incidents are small events in terms of the fire heat release rate (FHRR) and impact on life safety, but that large FHRR events can occur, with devastating loss of life. Small fire events are noted to be far from insignificant, particularly with respect to disruptions, injuries and sometimes loss of life.
In terms of major events, involving multiple casualties, there have been in the order of 10 to 15 such events globally over the past 100 years [2], which is a very small number considering the vast number of rail and metro systems operating. Many of these major events, where a railcar experiences a flashover, are a result of arson rather than a vehicle fault. As an example, a subway fire of 2003 in Daegu, South Korea, killed 198 people and injured 146 people. The fire started in one train car through an arson attack. The fire later spread to a second train that came from the opposite direction and stopped alongside the incident train. Post-incident analysis revealed that response procedures played a major part in this event because the second train should never have entered the station. The situation was exacerbated when the automatic fire detection and response system shut down the power supply to the trains, causing doors to remain closed, trapping 79 passengers inside the train. It is also noted that there was a lack of emergency equipment to be used for firefighting, which made the situation worse.

Small FHRR fire events due to vehicle faults, track fires or power system faults tend to be common. Some recent examples include the following:

- **New York City, June 2017**: A subway train derailed and a small fire started, possibly due to trash [3]. Around 800 people in the train were evacuated, a process which took over one hour. Occupants forced doors open during the evacuation, and people were exposed to smoke. No major injuries were reported.
- **Atlanta, May 2017**: Smoke filled a railcar traveling through a tunnel. There were no injuries reported but stations were closed for around two hours while passengers were evacuated. People on a train nearby also had to be evacuated. Passengers interviewed after the evacuation iterated that there was initial confusion about the appropriate course of action [4, 5]. The smoke that filled the train was caused by an arc of high voltage electricity [5]. The metro agency noted in statements that regular training is provided for their staff, and that a post-incident review was conducted to determine any corrective actions.
- **Washington, DC, January 2015**: Severe electrical arcing was found to be the cause of a smoke event that filled a tunnel and station with smoke on the Washington Metropolitan Area Transit Authority (WMATA) network [6]. The tunnel ventilation fan operation was not optimal in this event and as result all railcars filled with smoke, and in addition, passengers waited at least 35 minutes to evacuate because the train was stalled in the tunnel. As a result of smoke inhalation, there was one fatality from this incident and 90 people were injured [6]. Investigations by the National Transportation Safety Board (NTSB) found that although efforts were being made toward operational safety, that there were many areas for improvement, particularly related to equipment operability, and training and testing of operational personnel [7]. Work to update ventilation modes and improve operational responses is underway as a result of this incident and investigation [8]. Recognizing the risk, the NTSB also issued a directive to all transit agencies in the United States, recommending that all rail transit agencies conduct an audit of their systems to identify the state of repair of the tunnel ventilation, emergency procedures, training programs, and compliance with best practice such as NFPA 130 [9].

The minor incidents discussed above are examples of incidents that occur with reasonable frequency. This review shows that although the FHRR is quite small, typically at around 1 MW, the consequences in terms of human impact and disruption are serious. The review also highlights that the NTSB takes these incidents very seriously and also the need for a widespread check of current transit systems.

**Current US Experience**

A survey of 30 transit agencies in the United States was recently undertaken [10]. Six of the agencies were singled out for more in depth reporting. Five of the six agencies cited emergency ventilation systems being used as a part of their response to fire. NFPA 130 [1] specifies the requirements for a
modern rail tunnel system. However, several agencies acknowledge that their aging systems are often impeded by physical constraints that limit the ability to meet today’s standards. For existing systems the aspirational goal of rehabilitation projects is to bring them in compliance with NFPA 130 [9]. However, given that this is not always feasible, it is necessary for agencies to at least assess the performance of their existing system and bring it to a state of good repair.

Considering the existing system performance can reveal potential for improvement. For example, the Greater Cleveland Regional Transit Authority (GCRTA) found that although their system had an emergency ventilation system in place, the operations (always operated in exhaust) did little for smoke management if the fire location and egress path of passengers were not also considered [10]. Sound Transit in Seattle further stressed that making sure to blow the smoke away from passengers should always come first, even if this means going against the optimal direction for ventilation. It is noted that smoke is emphasized as being responsible for more harm than heat from a fire [10].

Beyond the use of emergency ventilation systems, passenger evacuation and safety are also dependent on the emergency response procedures set forth by the agencies that operate each tunnel system. Agencies such as Massachusetts Bay Transportation Authority (MBTA) and GCRTA that manage a mixture of transit options (heavy, light, commuter rail), also face the challenge of needing to customize procedures based on the type and location of incident train involved. Systems with heavy rail trains must factor the slowdown that occurs when passengers must descend from ladders to reach the track level for evacuation. As a result, rather than waiting to deal with the complexities involved during a fire emergency, these agencies focus on taking the proactive measure of preventing fires by vigilantly clearing the tracks of litter that can serve as ignition sources for fires. Reducing the potential of combustibles, and security considerations, led the Port Authority Trans-Hudson Corporation (PATH) to eliminate trash cans on its platforms so that trash would not be blown onto the tracks, and they replaced wood ties on the tracks with a non-combustible material [10]. Additionally, the PATH, GCRTA, and Sound Transit agencies all maintain close relationships with local fire departments and frequently conduct drills to train staff. WMATA tries to reduce passenger panic in its operational response by incorporating a delay before alarm announcements to allow time for an operator to verify that a fire emergency exists.

Transit agencies in the United States are following through on the NTSB recommendations following the WMATA incident [10]. Ventilation definitely plays a major role in FLS but the review here highlights that there are many other facets to achieving the best possible level of FLS in an existing system. In particular, the preventative and operational actions, which are relatively inexpensive compared with major ventilation upgrades, are seen as having potential for significant safety improvements.

**Approaches to Developing System Design Fires**

The design FHRR is a key input to a ventilation system design and the magnitude of the FHRR, the soot yield and the growth rate, all have major impacts on the outcomes during a fire in an underground facility. Ventilation systems for many existing facilities have been designed based on heuristics for the railcar FHRR, which do not fully take into account the fire potential of materials on board the railcar. Each rail system is unique in design, from the geometry to the interior materials lining the railcars. As such, the combustibility and potential FHRR vary from one system to another, and these factors should be considered when looking at a system ventilation rehabilitation.

Rail system fires can be classified into three categories: track fires (fires initiated in the undercarriage of a rail car), interior vehicle fires (fires initiated inside a train car), and station fires. Track fires are mostly caused by electrical issues or debris on the tracks and rarely escalate to include the entire railcar (refer above). Station fires can be due to a variety of reasons, not always controllable nor preventable, such as arson. Interior vehicle fires are the most likely to threaten passenger safety and smoke can spread out of the train car and into the tunnel, thereby impeding evacuation.
The interaction of an ignition source and interior materials of a train car dictate whether fire will spread beyond the ignition point and potentially involve the entire train to flashover or self-extinguish. With the advancement of computational technology, testing, and understanding of material properties, it is possible to approximate a custom design fire size for a given rail system based on rail car interior material testing and composition. Multiple studies have investigated the use of computer models, based on small-scale testing, to simulate fire in a system that would otherwise require large-scale testing. Results compared to historically established physical tests show that while it is possible to replicate the fire curve of individual materials, obtaining accuracy for the fire spread of a system involving many materials continues to be an area of further research and development.

The National Institute of Standards and Technology (NIST), in a series of studies conducted between the late 1990s and early 2000s, investigated the difference between basing fire growth and passenger evacuation on small-scale material testing, mockup testing of partial vehicle assemblies, and full-scale fire testing of an Amtrak coach rail car. The focus of these studies was the time it took to reach untenable conditions for passenger evacuation. On average, 13% agreement was achieved between the physical tests and computational model predictions. NIST determined that ignition source sizes of 25 kW to 200 kW were needed to propel flame spread [11].

NFPA 130 discusses conducting tests with a cone calorimeter [12] to obtain material properties for fire situations. Practical demonstrations of this, including use of the test results in CFD models are available [13]. It was found that a further calibration was necessary for a realistic model, thereby reaffirming the importance of physical testing on at least a scale model [13]. The method was applied to the Singapore Circle Line metro system, for the design of its emergency tunnel ventilation system. The ignition source used for the full-scale model was 200 kW and the analysis resulted in recommending a 5 MW design fire for the station and 10 MW design fire for the tunnels [13].

One method of categorizing fire hazard is to use a flame spread parameter, calculated based on outputs from cone calorimeter testing [14]. This is suggested as a screening tool to estimate whether materials on an interior of a rail car will support fire growth. The approach emphasizes the possibility, practicality, and benefits of performing small-scale fire testing via cone calorimetry to obtain material properties, in favor over the more costly, highly-customized, and complicated large-scale fire testing. Material properties are then used in pyrolysis computational models, which involve the interactions of multiple types of materials of the entire train car to predict flame spread over the system. The expectation is that once this approach is calibrated, it can be implemented to supplement the design fire development for a given system.

**Risk Assessment and Acceptance**

In much of the United States, transit systems were built prior to the current edition of NFPA 130, and therefore in some respects do not meet the criteria set forth by the standard. The aspirational long term goal of each rail system is to comply with NFPA 130, however, the standard recognizes that full compliance might not be achievable, and that maintenance of the existing performance should be sustained at a minimum [1].

Ventilation upgrades are not always cost-effective to develop, nor are they always acceptable to the community, particularly in built-up areas. For instance, a project to retrofit a ventilation plant in New York City was recently shelved due to community opposition to the neighborhood disruption it would have caused [15]. The project was noted to have been “on the shelf” for over 20 years and this made the safety aspect questionable to the community. In addition to community opposition, that project had an estimated cost in the order of $80 million to $96 million. Balancing out these requirements, the fact that limited resources (funding) might be available, the need to maintain the existing system, and that the level of safety is different throughout the network, requires an ongoing (live) risk-based approach to assess where to best allocate resources. The American Public Transport Association (APTA) has developed guidelines for fire safety analysis of existing passenger rail equipment [16]. This document identifies a method that stakeholders can
use to address four crucial elements; identification and prioritization of risks, development of action plans to reduce risk, measuring, monitoring and documenting, as well as maintenance of the action plan [16]. APTA provides a method to identify risks unique to a rail system based on fire location, train location, and the equipment being run during the fire scenario. Each fire scenario is scored based on frequency of the event occurring, and the consequence of the risk. The scores agreed upon for each risk are used to set priority for necessary action to alleviate or eliminate each hazard [16].

Though some risks may be mitigated to reduce the spread of fire or smoke, decrease ignition sources or improve the probability of early detection, APTA recognizes that there will always be an amount of residual risk [16]. Residual risk cannot be completely eliminated for a system, and some level must be accepted. APTA does not quantify how much risk is deemed tolerable, however, it notes that all stakeholders must agree upon the necessary actions to be taken to reduce risk as much as possible. APTA does not stipulate the timeframe at which such countermeasures to mitigate risk should be implemented, however, proper maintenance and tracking is expected to ensure risks are tended to in a timely manner [16]. For example, in the instance of the ventilation plant proposed in New York City [15], agencies must take into consideration not only the consequence of each countermeasure and where it stands relative to other risks, but public perception of such countermeasures. Though specific construction measures may not rank as high as other improvements, the public perception of heavy construction is that major improvements are being made. Therefore, strategies that require a heavy construction effort, and impose the most adverse effects on communities and businesses, need to be properly timed. Risk assessments are a delicate balance between agencies, passengers, crew and the surrounding communities. Timely identification and mitigation is necessary to assure that rail systems maintain a level of operation that is acceptable by standards, regulators and stakeholders.

INTEGRATED APPROACH TO RAIL SYSTEM VENTILATION REHABILITATION

An integrated approach to rail system ventilation rehabilitation is demonstrated in this paper. The framework and following sections demonstrate the application of this framework via a case study. Some points about each step include the following:

1. The first step involves characterizing the existing system in terms of current performance. It is unlikely that an aging system will satisfy modern equivalents, however, this provides a baseline that informs further considerations.
2. The second step involved considering options for improvement. This could include extra ventilation capacity, egress improvement, operational changes or fire prevention measures.
3. Step three advocates using risk assessment to provide a framework for informed decision making.
4. Finally, step four is a continuous improvement initiative whereby the first three steps are periodically repeated in order to keep decisions made relevant with respect to equipment condition, available funding and community expectations.

CASE STUDY

A case study is provided in the following sections to illustrate the integrated approach to rail system ventilation rehabilitation. The case study is assumed to be an existing US tunnel that was designed and built prior to release of modern fire safety standards such as NFPA 130. The geometry and main fire safety parameters of the existing system are described in Table 1 with key features shown as Figure 1. It should be noted that the case study is based on a fictitious tunnel that is not representative of any existing or planned infrastructure. For the case study it is assumed that the segment being investigated is in an urbanized environment which limits options for large-scale change to the tunnel envelope or surface connections. The tunnel segment is also considered crucial to business continuity and cannot be taken out of service for extended periods for construction purposes.
Table 1  Case study parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tunnel Geometry</strong></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>600 m</td>
</tr>
<tr>
<td>Width</td>
<td>10.8 m</td>
</tr>
<tr>
<td>Height</td>
<td>4.8 m</td>
</tr>
<tr>
<td>Tracks</td>
<td>2 tracks with solid dividing wall between tracks, see Figure 1</td>
</tr>
<tr>
<td><strong>Railcar</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Subway, predates modern standards such as NFPA 130</td>
</tr>
<tr>
<td>Consist</td>
<td>6 cars, total length of 140 m</td>
</tr>
<tr>
<td>Occupant load</td>
<td>40 people per car, 240 people total, population mix of male, female, child and elderly</td>
</tr>
<tr>
<td><strong>Evacuation</strong></td>
<td></td>
</tr>
<tr>
<td>Strategy</td>
<td>Portals using an elevated walkway</td>
</tr>
<tr>
<td>Walkway</td>
<td>0.9 m wide, constrained by tunnel/track geometry</td>
</tr>
<tr>
<td><strong>Ventilation</strong></td>
<td></td>
</tr>
<tr>
<td>Mid-point ventilation</td>
<td>66 m$^3$/s supply or 66 m$^3$/s exhaust, depending on location of train and fire</td>
</tr>
<tr>
<td>Activation</td>
<td>Manual activation by centralized control room</td>
</tr>
</tbody>
</table>

Figure 1  Case study geometry

CHARACTERIZE THE EXISTING SYSTEM

The first step in the analysis is to characterize the existing system in terms of the likely hazards and the existing performance of the fire safety systems. Aside from the geometry discussed above, the design FHRR and ventilation performance are typically the main elements when it comes to characterizing the existing system.

Design Fire Methodology

A key component for FLS design is the design fire. Modern versions of NFPA 130 place strict requirements on the materials used and their fire performance under standardized tests, however, for older rolling stock there may be less information regarding fire potential. Methods to predict the design fire vary from educated guessing (fire load divided by assumed, non-scientific, burn time based on previous experience), to cone calorimeter informed analysis (such as Duggan’s method), to CFD assessment, to full scale testing.

Fire testing on a full railcar is the most accurate method for determining fire behavior, but it is an expensive option that is rarely implemented. Small scale testing using the cone calorimeter, refer to Figure 2, has been used to characterize fire behavior of individual materials [17]. The simplest cone calorimeter based methods tend to overestimate the fire heat release rate because they assume all materials burn instantaneously, with the heat release rate informed by the cone calorimeter test. More
advanced methods improve on this, but still have a tendency to overestimate the fire growth rate and flashover potential.

Scale models of a railcar interior can be used to understand the interaction of materials during a fire and to help calibrate larger scale models such as a CFD model of a full railcar [13]. A CFD model can never replace a full scale railcar fire test, however, the calibrated model can help to understand the response of the materials to different kinds of ignition sources. NFPA 130 Annex D outlines the following steps to consider when developing a model to predict railcar fire profiles: 1) quantity and properties of accelerants; 2) fire characteristic of car interior materials measured according to ASTM E1354; 3) layout of the car interiors, including seating layouts, orientations, and dimensions; 4) bags and luggage carried by passengers; 5) overall thermal transmission value for vehicle body; 6) openings, including windows and doors; 7) oxygen levels; and 8) mechanical and natural ventilation.

CFD is the most advanced method available short of conducting full scale testing. It can predict a more realistic fire growth rate. Note that a critical input to a CFD analysis is the ignition source; with any railcar it is possible to reach a flashover condition (>10 MW) if a large enough ignition source is used, and key here will be stakeholder agreement to an appropriate level of ignition. Note that this discussion also assumes that the most critical scenario is a fire originating internal to the vehicle and that external fires are minor (1 MW) because of external material fire rating and hardening (i.e. floor can withstand ASTM E 119 test for 30 minutes or more). The interior scenario is assumed to be a deliberate event such as a minor arson event (newspaper) to more serious event (luggage or worse).

The methodology described above was used on a recent project to characterize the railcar fire potential. Railcar interior materials were understood to have been NFPA 130 compliant following a rehabilitation several years earlier. Tests of materials in the cone calorimeter were conducted, along with three mock-up scale railcar fire tests (using seats, flooring and wall panels). The tests were used to calibrate a full-scale CFD model of a railcar. The work included the following:

- Railcar seat materials (fiberglass reinforced polymers) were exposed to various ignition sources and did not burn in an uncontrolled way. Ignition sources included burning newspaper, gasoline, a blow torch, and a backpack. In all of the tests the seat material did not continue to burn once the primary ignition source was depleted.
- Tests on interior mock-ups (seats, flooring, walls), refer Figure 3, which showed that the fire did not readily spread, unless the ignition source was sufficiently large and located to concentrate heat through a more constrained fire plume. The FHRR was measured as part of the test to assist in calibration of a CFD model.
- Cone calorimeter tests were used to derive material properties of individual materials (ignition temperature, conductivity, heat capacity, density, heat of combustion, soot yield) and to derive heat release rate profiles of individual materials (i.e. heat release rate per unit area). The data were then used in CFD models of the mock-up. These models were used to help refine the material properties as part of a calibration process.
- Parameters from the final mock-up scale CFD models were used in a full-scale railcar model to estimate the worst-case (flashover) fire potential (growth rate and peak FHRR).
The outcome of this analysis was an understanding of the railcar fire potential; including the worst-case growth rate and peak FHRR, soot yield, heat of combustion, as well as the response of the system to common ignition sources. The tests showed that, in general, the railcar interior materials were unlikely to burn when exposed to minor arson fires, such as a burning newspaper or a small gasoline pool. These results were used to inform a characterization of fire scenarios for further analysis in CFD models and risk assessments. A key aspect of the definition of a fire scenario for risk assessment is that there is not one type of fire, but rather a spectrum of fires ranging from low to high hazard. Fires were characterized in terms of FHRR, growth rate and likelihood as described in Table 2 with fire hazard types (FHTs) of low, medium and high defined and carried forward into the rest of the analysis. Fire likelihoods were based on observation and assumptions, partly informed by testing and operational experience.

<table>
<thead>
<tr>
<th>Hazard severity (FHT)</th>
<th>Relative likelihood</th>
<th>FHRR range</th>
<th>Growth rate</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (L)</td>
<td>95%</td>
<td>&lt; 1 MW</td>
<td>T-squared, fast</td>
<td>Trash fire, electrical arcing event, minor arson</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>4.99%</td>
<td>&gt;1 MW to 5 MW</td>
<td>T-squared, medium</td>
<td>Major arson or equipment fault</td>
</tr>
<tr>
<td>High (H)</td>
<td>0.01%</td>
<td>&gt;20 MW</td>
<td>Profile, from CFD</td>
<td>Worst-case event</td>
</tr>
</tbody>
</table>

**Ventilation System Performance**

The first step in characterizing the existing ventilation system performance is gathering information about the installed equipment, and making assessments about the state of this equipment and how it is operated. This is likely to require gathering of design documents and commissioning results, if they exist, and undertaking site assessments of the components that make up the ventilation system. Site assessments could include taking airflow measurements in the tunnel to determine the actual performance of the existing, and aging, ventilation system [18]. This initial step is a key step in a rehabilitation project if details about the installed equipment and their condition are not well defined, and could also help to inform costs associated with bringing the existing system into a good state of repair.

The actual performance of the existing system prior to rehabilitation could be difficult to quantify with a level of certainty that can be carried forward into a reasonable future service life. The current condition of the equipment and any future deterioration might mean that the performance has or will become degraded compared to the as-designed performance. With this in mind, the existing system is characterized in terms of its designed performance rather than the performance as it stands prior to any rehabilitation being undertaken. This means that the analysis of the ventilation system performance is in terms of bringing the existing system into a good state of repair, thus providing a
baseline that can be used to inform alternative design options. Deterioration or operational deficiencies are accounted for when comparing alternatives in the risk assessment based on the site visit assessments undertaken to assess the condition of the existing equipment.

It is likely that a rail system requiring rehabilitation was designed without the use of modern analysis tools such as CFD and egress modelling. However, when it comes to characterizing ventilation system performance these tools are now readily available and relatively inexpensive. Using CFD models coupled with egress modeling, along with Subway Ventilation Simulation (SVS) analysis [19], provides a detailed understanding of the system performance taking into account the various fire scenarios, ventilation modes, timing, and evacuation characteristics.

For the case study in this paper, Fire Dynamics Simulator (FDS) version 6.5.3 [20] was used for the CFD modelling and this was coupled with FDS+Evac [21] to perform the evacuation analysis. The main inputs to the modelling are defined by Table 1 and Figure 1. FDS+Evac is particularly useful as it is intrinsically coupled to FDS, which means that the setup, execution and post-processing of the models can be scripted. This is advantageous when many models need to be run to inform the analysis of multiple alternatives. Different ventilation conditions were considered in the analysis including natural ventilation (zero pressure boundary in the FDS model), mid-point exhaust or supply (modeled with a fixed volume flow boundary in the FDS model) and longitudinal ventilation with jet fans (modeled using a fixed velocity boundary at the tunnel inlet).

Table 3 summarizes the outcomes from the ventilation system analysis of the existing system. For each scenario a score was calculated that is an indication of fire safety acceptability of that scenario. This metric could be based on multiple factors, however, for this case study the fractional effective dose (FED) was used. The calculation of the FED is as described in the FDS+Evac user manual [21] and it is output for each of the 240 agents in the model. As defined by ISO 13571 [22], an accumulated FED of 1.0 corresponds to a log-normal distribution of responses, with statistically 50% of the population expected to experience compromised tenability. A threshold criteria of accumulated FED > 0.3 translates to approximately 11% of the population being statistically susceptible to compromised tenability.

The maximum FED from each model was recorded and a score computed on a log scale basis:

\[ Score = S_{ij} = \left[ \log_{10}(\text{max FED}) \right] \times 100/3 \]  

If the maximum FED was less than 0.001 then it was automatically set to 0.001. With this scale, a low FED (0.001) would give a system ventilation score of 100 (best possible) and with an FED of 1, the score would be equal to 0 (worst possible). A log scale was used for computing the scoring because it enabled a better reflection of the scenario outcomes compared with a linear scale which did not show up any major differences. The denominator of 3 is necessary to normalize the log of the FED (which can be between 0 and 3). Given that the maximum FED is based on a single person, it is a reasonable approach to use a log scale this way; the system will give a good ventilation score if just one person is exposed to a little smoke, but it will give a poor score if one person has an FED of 1.0. This is appropriate because an FED of 1.0, even if it is only for one person, indicates a situation where it is likely that more people are exposed to smoke. The inverse applies for very low FED values.

From the outcomes in Table 3 it is seen that the existing system performance is reasonable for some of the low and medium hazards, but this is somewhat dependent on the fire location. These low and medium fire hazards are more probable and a good level of performance is expected for these hazard types. The performance is quite poor for the high hazard fire, but it should also be remembered that this hazard is less probable, which is not accounted for in the scoring. The scoring provides an indication only of the performance for each hazard type and it is the risk assessment that factors probability of these events to provide an overall performance appraisal.

When characterizing the ventilation system performance it could also be the case that it was not
originally designed for the fire scenarios being considered. This highlights the benefit of characterizing the design fire into a range of scenarios (low, medium, high). If a single design fire was applied, the system may be under- or over-designed relative to the FHRR, and this may distort the overall system appraisal.

However, note that an assessment where every possible fire scenario is analyzed was not conducted because the risk assessment methodology, discussed further below, does not require it. The risk assessment methodology, which assigns a score in proportion to ventilation system performance, is designed to allow the score to be assigned by the engineer, supported by as little or as much quantitative analysis as their judgement deems necessary. The advantage of this approach over an approach that analyzes all possible scenarios is that the engineer can run a few scenarios and then screen the system and the alternative concepts, thus allowing an efficient identification of the more attractive concepts for further development.

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>71</td>
<td>Smoke to W and people move E in clear air</td>
</tr>
<tr>
<td>2</td>
<td>L</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>59</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>Mid tunnel / W side of shaft</td>
<td>EV, smoke to E</td>
<td>23</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>Mid tunnel / E side of shaft</td>
<td>EV, smoke to W</td>
<td>46</td>
<td>Smoke to W, captured at shaft</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>91</td>
<td>Smoke to W and people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>65</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>Mid tunnel / W side of shaft</td>
<td>EV, smoke to E</td>
<td>14</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>Mid tunnel / E side of shaft</td>
<td>EV, smoke to W</td>
<td>52</td>
<td>Smoke to W and BL to E</td>
</tr>
<tr>
<td>9</td>
<td>H</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>70</td>
<td>Smoke to W, people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>10</td>
<td>H</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>1</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>11</td>
<td>H</td>
<td>Mid tunnel / W side of shaft</td>
<td>EV, smoke to E</td>
<td>0</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>12</td>
<td>H</td>
<td>Mid tunnel / E side of shaft</td>
<td>EV, smoke to W</td>
<td>0</td>
<td>Smoke to W and BL to E</td>
</tr>
</tbody>
</table>

Abbreviations:
- FHT = fire hazard type
  - L: <1 MW fast growth
  - M: ≤ 5 MW medium growth
  - H: ≥ 20 MW arson fire
- W = west
- E = east
- EV = Exhaust (66 m³/s)
- SV = Supply (60 m³/s)

Remarks:
- Column “Ventilation” notes the design basis behavior of smoke.
- Column “Outcomes” notes the actual behavior.
- Column “Score” is computed as noted by equation 1.

OPPORTUNITIES FOR IMPROVEMENT

Developing Alternatives

Opportunities for improvement as part of a rehabilitation project are likely to be system-dependent. However, a few items that require consideration are (1) the existing performance, (2) the operational strategy, (3) physical limitations (4) budgetary constraints (5) business continuity requirements and (6) mandatory regulatory requirements. The weight that is applied to each of these considerations is also going to be system-dependent, but this at least provides prompts of some key items to consider.

In terms of the case study, the as-designed performance of the existing system has been characterized in the previous section. However, this does not necessarily reflect the current condition of the equipment or other operational deficiencies. The opportunity here lies in bringing this equipment into a good state of repair to reinstate the original ventilation performance. There is also an opportunity to adjust the operational strategy and see if this provides a benefit. The later could be as simple as improving operator training or reconfiguring the operational modes to achieve a better outcome.

In developing the case study example it was defined that large-scale structural works were not
possible due to the urban environment above and that business continuity needed to be considered as the system could not be out of service for long periods. These would be likely constraints on an actual rail system. With this in mind, major changes to the ventilation arrangement are not considered further, neither are changes to the evacuation strategy such as widening the walkway. While this does limit some of the alternatives that could be considered, there are other opportunities worth considering and the focus here is on ventilation alternatives.

There is a solid dividing wall between the tracks that has a break at the mid-point ventilation station. This dividing wall may be beneficial in terms of limiting smoke spread for certain scenarios, but may reduce the efficacy of the ventilation system as the railcars act as a pinch point within the tunnel, affecting the system aerodynamics. Assuming the dividing wall is only partially load-bearing, openings could be added to make a porous wall with an open area of 12%. This may reduce smoke spread because it effectively opens the tunnel (removes the rail vehicle pinch point) and the system may be more effective for some scenarios.

Longitudinal ventilation is also a possible alternative. Assuming there is sufficient headroom for jet fans to be installed, the fans would provide good ventilation performance, albeit at a significant cost. This alternative might be representative of an NFPA 130 design where the longitudinal ventilation provides a clear evacuation path on one side of the fire and the direction of operation is dependent on the fire location in the train.

Given the tunnel is relatively short at 600 m, there might also be an opportunity to utilize a natural ventilation solution. This would be operationally simple with reduced ongoing maintenance and capital costs. From an operator’s point-of-view this may be preferred, but external wind effects need to be considered, as well as any requirements for intervention and post-incident recovery.

Analysis of Selected Alternatives

Bringing the system into a good state of repair has already been characterized and this is carried forward into the risk assessment where the state of equipment and operational considerations are factored into the performance of the system prior to rehabilitation. The system prior to rehabilitation is denoted Alternative 1 and the system being bought into a good state of repair is denoted Alternative 2.

The other alternatives selected for further analysis include the porous center wall (Alternative 3), longitudinal ventilation with jet fans (Alternative 4) and natural ventilation (Alternative 5). These alternatives were subjected to the same analysis methodology as the existing system, with specific scenario selection suitable for these alternatives. Fire scenarios for analysis were selected using a small subset of all the possible combinations of fire severity and location.

Table 4 provides results for the porous center wall. The improvement in smoke management and egress outcomes for the scenarios tested is negligible. Analysis for the longitudinal ventilation with jet fans is provided in Table 5. The scores based on FED are improved to a moderate extent, except for one scenario, associated with the high severity fire hazard, where there is a large improvement in the outcome. Finally, for the natural ventilation solution a range of winds were also considered given that this alternative is more susceptible to external wind conditions. The analysis for this alternative is given as Table 6. Results show a general drop in performance compared with ventilated cases, especially for unfavorable wind directions.

Final results, refer to Table 7, are obtained from Table 3, Table 4, Table 5 and Table 6 by averaging the data obtained from analysis. It is noted that the data are not comprehensive in terms of the scenarios; alternative ventilation approaches were considered only for a train located west of the vent plant. However, assuming that the results would trend the same way for different locations, the results from Table 3 are used to inform judgement on adjustments to performance scores. In general, when a train was located toward the center of the tunnel risk scores are poorer by around 30 to 40
points, and considering that the “mid tunnel” region represents no more than one third of the tunnel length, an average point reduction of 10 to 15 points was observed and applied to all the results.

Table 4  Alternative 3 – porous center wall

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>L</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>78</td>
<td>Smoke to W and people move E in clear air</td>
</tr>
<tr>
<td>14</td>
<td>L</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>79</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>15</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>89</td>
<td>Smoke to W and people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>16</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>86</td>
<td>Smoke to E and BL to W</td>
</tr>
<tr>
<td>17</td>
<td>H</td>
<td>W tunnel / W end train fire</td>
<td>SV, smoke to W</td>
<td>86</td>
<td>Smoke to W and people move E in clear air, some late BL to E</td>
</tr>
<tr>
<td>18</td>
<td>H</td>
<td>W tunnel / E end train fire</td>
<td>EV, smoke to E</td>
<td>81</td>
<td>Smoke to E and BL to W</td>
</tr>
</tbody>
</table>

See Table 3 for abbreviations and notes

Table 5  Alternative 4 – longitudinal ventilation with jet fans

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>L</td>
<td>W tunnel / W end train fire</td>
<td>JFV, smoke to W</td>
<td>85</td>
<td>Smoke to W and people move E in clear air</td>
</tr>
<tr>
<td>20</td>
<td>L</td>
<td>W tunnel / E end train fire</td>
<td>JFV, smoke to E</td>
<td>92</td>
<td>BL to W reduced</td>
</tr>
<tr>
<td>21</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>JFV, smoke to W</td>
<td>79</td>
<td>BL to E reduced</td>
</tr>
<tr>
<td>22</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>JFV, smoke to E</td>
<td>97</td>
<td>BL to W reduced, more smoke to E</td>
</tr>
<tr>
<td>23</td>
<td>H</td>
<td>W tunnel / W end train fire</td>
<td>JFV, smoke to W</td>
<td>86</td>
<td>BL to W reduced</td>
</tr>
<tr>
<td>24</td>
<td>H</td>
<td>W tunnel / E end train fire</td>
<td>JFV, smoke to E</td>
<td>82</td>
<td>BL to W reduced, more smoke to E</td>
</tr>
</tbody>
</table>

See Table 3 for abbreviations and notes, JFV = jet fan ventilation, sized to achieve critical velocity for >20 MW fire

Table 6  Alternative 5 – natural ventilation

<table>
<thead>
<tr>
<th>ID</th>
<th>FHT</th>
<th>Train / fire location</th>
<th>Ventilation</th>
<th>Score</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>NV, no wind</td>
<td>66</td>
<td>Smoke moves to E, beyond vent plant</td>
</tr>
<tr>
<td>26</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>NV, no wind</td>
<td>15</td>
<td>Smoke moves to W, does not move to E</td>
</tr>
<tr>
<td>27</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>NV, wind to E</td>
<td>11</td>
<td>Smoke moves to E</td>
</tr>
<tr>
<td>28</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>NV, wind to E</td>
<td>91</td>
<td>Smoke moves to E</td>
</tr>
<tr>
<td>29</td>
<td>M</td>
<td>W tunnel / W end train fire</td>
<td>NV, wind to W</td>
<td>97</td>
<td>Smoke moves to W</td>
</tr>
<tr>
<td>30</td>
<td>M</td>
<td>W tunnel / E end train fire</td>
<td>NV, wind to W</td>
<td>18</td>
<td>Smoke moves to W</td>
</tr>
</tbody>
</table>

See Table 3 for abbreviations and notes

Table 7  Final averaged risk scores for each ventilation option (rounded to nearest 10)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>50</td>
<td>70</td>
<td>80</td>
<td>40^</td>
</tr>
<tr>
<td>M</td>
<td>60</td>
<td>70</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>H</td>
<td>20</td>
<td>30</td>
<td>70</td>
<td>10^</td>
</tr>
</tbody>
</table>

^Simulations were not run for these cases, but given generally observed poor performance this scheme was given a score 10 points worse than the worst result from Alternative 2 simulations.

INFORMED DECISION MAKING

Risk Assessment

The analysis for each alternative gives an indication of the performance for each hazard type, but does not factor in the probability of these hazards occurring. This could be misleading for a rehabilitation project where hard constraints limit the practical improvements that can be made. For instance,
Aspirational goals around achieving NFPA 130 equivalent performance may not be realistic and there needs to be a framework to demonstrate that the rehabilitated project has achieved a reasonable balance between practicality, cost and performance, and that the residual risk is acknowledged and monitored.

A risk framework has been developed for rehabilitation projects that provides this framework by comparing the benefits and costs associated with a range of alternatives (Alternatives 3 to 5), and comparing these to doing nothing (Alternative 1) and bringing the system into a state of good repair (Alternative 2). This allows aspirational goals such as NFPA 130 to be included and assessed, but also other incremental improvements that could be staged over time when budgets and other opportunities permit.

An important aspect of the risk framework is the semi-quantitative nature of the assessment. While the inputs could be informed by detailed analysis, they could also be developed through stakeholder workshops with expert judgement. Ultimately the framework could incorporate detailed or qualitative inputs depending on the stage, complexity or requirements of a rehabilitation project. This flexibility also enables operators to carry the risk assessment forward, monitor the residual risk and identify opportunities for improvement.

The risk framework consists of a range of score-cards that can be tailored to a particular project. These score-cards could be based on elements such as ventilation performance, evacuation provisions, or any other element that impacts fire safety. A weighting can then be applied to each score-card if a particular element is deemed to have more influence on the outcome (e.g. smoke management can be given a greater weighting). When these score cards are combined they provide an overall indication of the FLS performance of an alternative that can be compared to other alternatives.

A simplified version of the risk framework is provided below in order to illustrate the scoring as applied to the case study herein, which was based solely on ventilation performance. For the analysis of the different alternatives a score was given out of 100 for the low, medium and high hazards (refer to Table 7). The higher the score, the better the alternative was in terms of FLS. This score, however, does not take into account the state of the equipment or operational assumptions.

A fire hazard score (FHS) is defined where a higher number denotes a potentially higher consequence and vice-versa. This takes into account the consequences of an unmitigated hazard. That is, without any fire safety provisions what an order of magnitude consequence could be for each hazard type. The score for an alternative reduces the unmitigated hazard taking into account the operation and condition of the equipment. The FHS used for the case study is calculated by Equation 2. This equation factors the unmitigated hazard score \(H_j\) by accounting for the relative hazard associated with the alternative (i.e. \((100 - S_{i,j} \alpha_{i} \beta_{i})/100\)). This means that if an alternative achieves a near perfect score (e.g. \(S_{i,j} \alpha_{i} \beta_{i} \rightarrow 100\)), then the alternative is successful at mitigating the hazard. Conversely, if the alternative has little effect on the outcome (e.g. \(S_{i,j} \alpha_{i} \beta_{i} \rightarrow 0\)), then the unmitigated hazard remains largely unchanged.

\[
FHS_{i,j} = \frac{H_j}{100} \left(100 - S_{i,j} \alpha_{i} \beta_{i}\right),
\]

where,

- \(FHS_{i,j}\) is the FHS for alternative \(i\) applied to hazard \(j\) (mitigated hazard; low, medium and high hazards),
- \(H_j\) is the FHS before the scoring is applied to hazard \(j\) (unmitigated hazard), for the case study \(H_l=10, H_m=100,\) and \(H_h=1000\),
- \(S_{i,j}\) is the score for alternative \(i\) as applied to hazard \(j\) (value between 0 and 100) (for the case study, this is based on the analysis in the previous sections).
operation factor to account for operational considerations associated with alternative \(i\) (e.g. procedural, training, etc.) (value between 0 and 1) (for example, well-defined procedures and well trained staff would be 1), and

condition factor to account for the condition of equipment associated with alternative \(i\) (value between 0 and 1) (for example, new equipment would be 1, faulty equipment would be closer to 0).

Once the FHS is computed for each hazard, the overall fire risk score can be calculated. Risk is typically defined as the product of consequence and likelihood. The order of magnitude consequences are defined by the FHS for each hazard type. The likelihood of each hazard type occurring \((P_L, P_M, P_H)\) can be informed by system fire statistics or some other relevant source. For the purposes of the case study the probability was informed by design fire considerations (refer to Table 2). The following equation gives the overall fire risk score \((FRS)\) for the alternative:

\[
FRS_i = FHS_L P_L + FHS_M P_M + FHS_H P_H
\]  

For each alternative a cost is also assigned. This cost could be based on detailed quantity surveying of the alternatives or an order of magnitude cost calculation. For the case study, order of magnitude cost estimates have been used. This cost for each alternative is then calculated as millions of dollars per fire by taking into account the frequency of each FHT.

Figure 4 shows an example of the risk assessment output as applied to the case study example. In this example the current condition assumes that the equipment is always operated appropriately and that 80% of the time the aged equipment will function. The FRS has been normalized by the results for Alternative 4 as this alternative represents an NFPA 130 compliant option. While the risk is lowest for the NFPA 130 design it has the worst outcome in terms of the cost versus benefit, which needs to be considered when there are only finite resources available. The natural ventilation option has the best cost versus benefit score, but this option is least compliant with NFPA 130 since there is now no ventilation where previously ventilation was provided. This option would not be acceptable from a community perspective, where there would be an expectation to at least keep the FLS ventilation equipment in good repair. The result that therefore is most acceptable is a rehabilitation effort to bring the equipment to a state of good repair (Alternative 2).

**Decision Making**

The result of the risk analysis shows the cost/benefit performance of the different options relative to a benchmark tunnel or station. It may not be possible to achieve NFPA 130 compliance and there is a need to accept and manage some level of residual risk, a situation that is acknowledged in guidelines published by the American Public Transport Association (APTA) [16]. Ranking of options relative to a benchmark is helpful because it allows the risk analysis to become a live analysis that can help to look ahead and plan for allocation of resources in the future in the most cost and safety effective ways possible.

It is noteworthy that risk analysis should never be based on cost versus benefit alone. This point was highlighted in the case study above where the best option for cost versus benefit was the least safe and would not be acceptable to the community because: 1) It is reducing safety relative to the current situation, and 2) It could be perceived as “rolling the dice” with respect to public commuter safety. That said, a decision also should not be made on the safest option alone because this is potentially a very inefficient allocation of resources. The approach shown here needs balanced risk decisions to be made based on cost, community requirements (such as NFPA 130), and overall level of safety.
Ventilation systems form an integral part of the fire-life safety systems for underground rail or metro systems. For older systems there is a need to assess the condition of equipment and assess options for rehabilitating or upgrading performance to try to meet present day standards. It is not always possible to meet present-day standards in an existing system and therefore an approach to determination of the best option for rehabilitating a metro ventilation system needs to combine railcar fire characteristics, CFD and egress analysis, and risk analysis. Existing rail systems are large and complex systems, and a full quantitative assessment of all the factors would be a very significant undertaking. A method was therefore developed with the objective of simplifying the process while still providing meaningful data for making informed decisions. The method includes the following steps:

1. Characterise the existing system performance (design fire and ventilation system effectiveness).
2. Consider options for improvement. This could include extra ventilation capacity, egress improvement, operational changes or fire prevention measures.
3. Conduct risk assessment to provide a framework for informed decision making.

The key part of the method is that it is semi-quantitative; a scoring system is developed which is informed by a mix of analysis (CFD and egress) and judgement. This score-based approach to risk assessment introduces the potential to not rely on massive amounts of analysis to generate or update a risk assessment; an owner can use as little or as much analysis as the situation requires. In contrast to a full quantitative risk assessment method, this method allows for efficient early phase screening of concepts and more refined analysis of options further along in a project, if necessary. A short tunnel with ventilation was analysed to demonstrate application, and it was seen that it is possible to develop an assessment that provides sufficient detail to inform an upgrade/rehabilitation design decision, with minimal quantitative analysis.

In conclusion, the method of assessment demonstrated herein, and the flexibility of analysis input can
enable an effective assessment of ventilation system performance, costs and risks. The method’s efficiency also makes it possible to adjust the risk assessment as years advance, adjusting the input parameters related to training, condition of equipment and observed events, and costs as the system ages and is improved, thus allowing prioritization of resources between maintenance, rehabilitation and upgrades related to FLS.

REFERENCES