Tunnel Ventilation Requirements for Underground Rail Crossovers

S. M. O’Gorman

1WSP Parsons Brinckerhoff
680 George St, NSW 2000
AUSTRALIA
E-mail: ogormans@pbworld.com

Abstract: In longer underground rail networks, operational needs may require an underground crossover. These crossovers provide a means for operators to manage service disruptions, but when built underground can come at a significant cost penalty. Life safety strategies and infrastructure for rail tunnels are well developed and documented in various international standards, guidelines or best practice studies. The ventilation requirements for underground crossovers are less well defined and vary depending on the railway and the jurisdiction.

An underground crossover aerodynamically connects two unidirectional tunnels. The crossover itself is typically in a cavern or box structure. Smoke control strategies are heavily dependent on the ventilation infrastructure provided as well as the interface with train operations and the project’s egress strategy. The impact of the ventilation strategy and infrastructure selected for a given project can significantly impact the size of the underground structures and the eventual cost of the project. This paper will give guidance on how the characteristics of the railway and the railway operations affect the choice of ventilation requirements for an underground crossover. It will also outline the various options available to the ventilation designer for a given set of requirements with the objective to minimize costly underground construction where it is not warranted by a particular railway system.

Keywords: Tunnel Ventilation, Fire Life Safety, Underground Crossovers.

1. INTRODUCTION

In longer underground rail networks operational needs may require an underground crossover. These crossovers provide a means for operators to manage service disruptions, but when built underground can come at a significant cost penalty. Life safety strategies and infrastructure for rail tunnels are well developed and documented in various international standards, guidelines or technical papers. Typically, modern rail tunnels are unidirectional and provided with longitudinal ventilation, egress paths/walkways either elevated or at track level and ancillary systems such as emergency lights and hydrant systems. For long tunnels an egress point to the surface or cross passages to a non-incident tunnel tube are provided. The presence of an underground crossover makes these provisions significantly more complicated, and the strategies for dealing with them are less well developed across the globe.

Underground crossovers can significantly impact on the effectiveness of the ventilation system in the case of a fire emergency in tunnels or stations adjacent to the crossover. The ventilation system needs to be designed specifically to manage the impact of the crossover. An underground crossover aerodynamically connects two unidirectional tunnels which increases the risk of smoke spread between tubes and into other areas of the underground rail network as well as making it significantly more difficult to achieve the required longitudinal airflows in the tunnels.

Given the complexity of a crossover and the lack of specific requirements there can be a tendency to apply an overly onerous ventilation requirement to a specific project. The purpose of this paper is to identify the risks created by an underground crossover, identify some of the more common options for ventilating a crossover and provide a methodology to assess which option is best suited to an individual rail network.
1.1. Underground Crossovers

Figure 1 shows two examples of underground crossovers. As stated above they are typically used to help operators manage service disruptions in an underground railway and are becoming increasingly common, especially in long networks or networks with high train frequency requirements. The crossover itself is relatively standard, however, it requires considerable space. Typically, an underground crossover is constructed in a large cavern, or in a cut and cover box creating a large tunnel cross sectional area and cross connecting two separate tunnels. The connection between the two tunnels can be minimized by walls on either side of the crossover that extend into the box or cavern, but still an interconnection will exist due to the required functionality of the crossover.

The preferred location of a crossover is adjacent to the station so that the ventilation system can be built into the station construction, utilising the station to transfer air from the tunnels to the surface and vice versa. If a crossover is located remotely from a station, then air control becomes more difficult or dedicated air shafts are needed to the surface. This paper will only focus on the case of a crossover directly adjacent to the station, although several conclusions of this study are applicable to all crossovers.

2. VENTILATION REQUIREMENTS FOR UNDERGROUND CROSSOVERS

2.1. Ventilation Requirements for Typical Rail Tunnels

The priority in a fire in an underground railway is to egress passengers and staff from the fire incident to a place of safety. Typically, in modern railways the strategy is to get the incident train to the nearest station where egress provisions are the greatest. For trains stopped or disabled in tunnels the strategy is to use a combination of walkways, lights and ventilation to provide at least one clear egress path for passengers and staff to escape the fire incident [1].

The ventilation system is typically used in a unidirectional rail tunnel to provide a clear egress path by managing the spread of smoke through the tunnel. Longitudinal ventilation uses an airflow, typically in the direction of train travel, to limit smoke to downstream of an incident providing a path clear of smoke upstream of the train. The direction of smoke movement can vary depending on the strategy adopted and how many trains are present in a ventilation section. For example, if two trains are in a ventilation section and the rear train is on fire, if both trains are unable to move a ventilation direction opposite to the direction of train travel may be preferable. Emergency services may also reverse the direction of ventilation to suit their operational needs.

These objectives and strategies typically lead to the following ventilation requirements [1] [3]:
- Longitudinal ventilation over the incident train greater than or equal to the critical velocity
- The non-incident tunnel may need to be protected from smoke spread if cross passages and the non-incident tunnel are a key element in the egress path.
- Smoke may be required to be limited to the incident ventilation section to prevent smoke spreading into an adjacent station or tunnel.
- The ventilation direction may need to be reversible.

2.2. NFPA 130

The US standard NFPA 130 is not mandated internationally but is commonly used as an international benchmark. It has several general and specific requirements for tunnels and stations. It has the following high level requirements for emergency ventilation systems:
- Provide a tenable path along the route of egress
- Provide sufficient airflow to meet critical velocity
- Accommodate the maximum number of trains that could be between ventilation shafts in an emergency (one is recommended in the appendix)
- The system shall be designed to move air in each direction as required to provide the needed
2.3. Assessing Ventilation Requirements

The above discussion of requirements and objectives for a typical rail tunnel can be extended to risks that may need to be managed by a ventilation system in the case of an emergency in a tunnel where an underground crossover is present. These risks can be summarised below:

1. Risk of smoke impacting non-incident trains in the crossover
2. Risk of smoke impacting trains in the non-incident tunnel
3. Risk of smoke entering the station adjacent to the crossover
4. Risk of not achieving critical velocity in the incident tunnel due to the presence of the crossover

3. EMERGENCY SCENARIOS AND VENTILATION OPTIONS

In this section, typical ventilation options for dealing with an underground crossover are introduced followed by a qualitative discussion of their ability to manage the four risks outlined above.

3.1. Ventilation Options

This paper presents three options for managing the ventilation at a crossover. Many more variations on these configurations exist but these three options were chosen because they’re commonly used in a range of jurisdictions to manage smoke movement around a crossover in an emergency.

- **Option 1** – The station tunnel ventilation fans adjacent to the crossover are used with the exhaust/supply connections to the tunnel on the station side of the crossover. This is the simplest configuration.
- **Option 2** – A ducted ventilation system, utilizing the station tunnel ventilation fans, with exhaust/supply connections to the tunnel on both the station and tunnel side of the crossover. This option may be the costliest as it requires a ducted connection and may impact the size of the crossover cavern.
- **Option 3** – Option 3 has a similar supply/exhaust arrangement as option 1 but jet fans are utilized in the tunnels to balance airflows around the crossover. This option is potentially cheaper than option 2, however, it does require some maintainable items being placed within the tunnels. Jet fans can also have difficulties balancing airflows under changing fire conditions which may require complicated control strategies.

3.2. General Underground Rail Scenarios

The fire scenarios chosen for study should be chosen very carefully for each project, should be relevant for the characteristics of that project and should be agreed with stakeholders during the design process.

Underground rail fires are rare, especially with the advancement of modern rolling stock and tunnel infrastructure. A risk assessment may be used to identify the likelihood of a fire event and the severity of that fire event. Typically, smaller garbage or arson fires of the order of 0.5-1MW are the most common fire types with fully developed fires in the range of 10-20MW occurring rarely. However, the ventilation system is usually designed for what is considered the most onerous fire size, and called the “design fire”.
Likewise, the likelihood of an incident train being stopped in a tunnel and not allowed to proceed to a station for egress is also rare in a modern railway. This would require the failure of an element of the rolling stock to occur at the same time as a fire event. The argument is that the fire may affect the rolling stock, stranding it in the tunnel. Given fire separation provided on modern rolling stock even this scenario has become less likely. However, there are many railways in the world which still use old rolling stock, have provisions for passengers to stop the train in a tunnel in an emergency without operator confirmation or have trains routinely stopping at signals in an underground rail network. As such the ventilation design typically allows for an incident train stopped in an underground tunnel.

3.3. Crossover Scenario

The underground fire scenario that impacts a crossover is for a fire on an incident train in the tunnel adjacent to a crossover. In this scenario, the train can either be approaching the crossover or leaving the crossover and is unable to get to the next station (for whatever reason).

This scenario is similar to a typical rail tunnel fire incident and so it is assumed that the incident tunnel will be ventilated in accordance with the agreed strategy for the rest of the network. For this paper, it is assumed that longitudinal ventilation is provided over the incident train with the option to reverse the ventilation direction if required.

3.3.1. Ventilation Towards the Crossover

If the smoke is moved towards the crossover (leaving the upstream direction clear of smoke for egress) the performance of the various tunnel ventilation options is shown in Fig 1. In this scenario, several questions need to be considered which relate to the risks established in section 2.4 including:

I. Does smoke entering the crossover impact non-incident trains or egress within the crossover area?
II. Will smoke enter the non-incident tunnel tube from the crossover?
III. Will smoke enter the station on the other side of the crossover impacting egress from the station?

For question 1, in the first ventilation option smoke is moved through the crossover to the exhaust point. It is extremely difficult to justify that if a non-incident train is present in the crossover that it will be protected from the effects of the smoke. The third ventilation option will perform similarly. In this case the smoke is still moved through the crossover to the exhaust point.

For the ventilation option with a ducted connection to the tunnel side of the crossover, smoke will be exhausted prior to entering the crossover. In this case, there is a high likelihood, if the ventilation system works as designed, that any non-incident train present in the crossover itself will be protected from the effects of the smoke. A tenable path of egress back to the station will be available to passengers on the non-incident train.

For question 2, it can depend on the operation of the ventilation system. However, with ventilation option 1 and 3 smoke will likely be present in the crossover presenting a risk of smoke impacting on the non-incident tunnel. This risk can be mitigated by operating the ventilation system in the non-incident tube to provide some “pressurisation”. This will likely impact the configuration of the ventilation system at the upstream station and may impact the sizing of the jet fans in the case of option 3. For ventilation option 2 the smoke is exhausted prior to entering the crossover. In this case the risk of smoke contaminating the non-incident tube is low.

The answer to question 3 depends on the design of the station and its smoke management infrastructure (i.e. is there an overtrack exhaust system present). However, it is considered much easier to keep smoke out of the station if the smoke is exhausted prior to entering the crossover as in Option 2. For option 3 it can be difficult to balance the jet fans effectively in an emergency because the required thrust for accurate air flow balance will vary with the fire size and even with time as the fire grows. As such there is a risk a jet fan based system will not be robust for all the different emergency scenarios.
If the smoke is moved away from the crossover the risk of contaminating the non-incident tube (through the aerodynamic connection created by the crossover) is not present if sufficient longitudinal velocity is provided by the ventilation system. Likewise, the risk of smoke contamination of the downstream station is no longer specific to the crossover and is similar to the case of the typical tunnel. However, the aerodynamic connection between the tunnels created by the crossover does make it significantly harder to achieve critical velocity in the incident tunnel compared to a typical tunnel section. This is because air is free to flow into the non-incident tunnel as well as multiple paths back into the upstream station, complicating the control of the air movement. Figure 2 shows the performance of the three ventilation options under this scenario.

For ventilation option 1 and 3 the air supplied by the upstream station is free to move in the direction of the incident tunnel, the non-incident tunnel and back into the upstream station. As a result, it is likely that more air will need to be supplied in order to achieve critical velocity in the incident tunnel. This is especially the case for downstream stations with no PSD’s that may reduce the effectiveness of the exhaust at the downstream station. In option 3 it can be argued that the jet fans will be able to compensate for the additional air paths by providing the necessary thrust in the incident tunnel to achieve the required airflow. For the second option air is supplied directly to the incident tunnel. Although the crossover can complicate the airflow paths it becomes similar in nature to a typical tunnel supplying air adjacent to a non-PSD station. In this case, it can be easier to control the airflow.
compared to option 1 but there may still be difficulties depending on the capacity of the ventilation system and the tunnel characteristics.

### 3.4. Summary of Ventilation Options

Table 1 summarises the risk of smoke spread in and around the crossover for the three different ventilation options.

<table>
<thead>
<tr>
<th></th>
<th>1 - risk of smoke in the crossover</th>
<th>2 - risk of smoke in the non-incident tunnel</th>
<th>3 - risk of smoke in the adjacent station</th>
<th>4 - risk of not achieving critical velocity away from the crossover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Option 2</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Option 3</td>
<td>No</td>
<td>Yes*</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

*Jet fans may have difficulty balancing airflows in some scenarios
4. IMPACT OF RAILWAY CHARACTERISTICS

Section 2.4 outlined some risks that a ventilation system should aim to manage in the case of an emergency. Table 1 is a high-level summary of the ability of the three ventilation options to manage those 4 risks. However, not all risks are applicable to every railway. This section describes qualitatively the potential impact of the railway on those risks.

4.1. Risk of Smoke in the Crossover

For item 1, it would be unlikely that a train would be stopped in a crossover if a train is heading towards the crossover. It’s more likely the train would be moving into the station or potentially be stopped at a signal within the tunnel itself. If the incident train is heading towards the crossover when it is stopped then this question would be dictated by the broader question related to trains in a ventilation section. If only one train is allowed in a ventilation section, then it is unlikely a train will be downstream of the fire incident. If two trains are allowed, then the response would be like a typical tunnel section and if the incident train is upstream of the non-incident than the ventilation direction should be away from the crossover.

If the incident train is moving away from the crossover when it is stopped then any non-incident train should be dealt with as above with the ventilation direction away from the crossover if a non-incident train is stopped in or near the crossover.

As a result, during typical operations leading to an emergency operation it is highly unlikely that a non-incident train will be stopped in the crossover itself. However, there are some extremely rare operational cases during degraded operations, and managed train movements, were trains may be near each other in the crossover and adjacent tunnel. This is more likely to occur with rail networks with long tunnels and high train frequencies with >1 train in a ventilation section.

4.2. Risk of Smoke in the Non-incident Tunnel

Item 2 can be assessed in a similar manner. However, it is likely that a non-incident train will be present in the non-incident tunnel if a fire occurs in the incident tunnel. The number of non-incident trains will depend on the length of the tunnels and the number of trains allowed in a ventilation section. If it can be shown that the non-incident trains can continue out of the non-incident train to stations further along the line, then no special provisions for the crossover are required. However, if a failure or de-energization of the traction system in the incident tunnel affect the non-incident tunnel then a level of protection needs to be provided to the non-incident tunnel. Similarly, if cross passages connecting the incident and non-incident tunnel are a key means of egress from the incident tunnel then some form of protection of the non-incident tunnel may be required.

Metro systems with short tunnels and or low train frequencies and only 1 train in a ventilation section are less likely to have stranded non-incident trains in the non-incident tunnel compared to systems with longer tunnels and high train frequencies. This will vary depending on the train operations and will also be dependent on the sectioning of the traction power system.

4.3. Risk of Smoke in the Non-incident Station

For item 3 it is good practice to prevent smoke from an incident tunnel entering the station. Other trains, waiting passengers or emergency responders may be present at the station. However, under some conditions smoke entering the station can be dealt with by the station smoke control system maintaining tenable conditions on the platform.
4.4. Summary of Railway Characteristics

Table 2 shows a summary of the impact of some railway characteristics on the risks required to be managed. This is an indicative list only and each element should be analyzed on a case by case project basis. The requirements of table 2 can be used in conjunction with Table 1 to identify an appropriate ventilation system configuration for a given project. For example, a high frequency rapid transit network with long tunnels and >1 train in a ventilation section may require the use of a ducted ventilation system (Option 2) to manage the increased risk of the crossover. However, a rapid transit system with short tunnels, 1 train per vent section and the ability to drive out non-incident tunnel trains may only require a very simple crossover ventilation system (Option 1).

<table>
<thead>
<tr>
<th>Railway Characteristic</th>
<th>Parameter</th>
<th>Risk to be managed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Length</td>
<td>Long</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td></td>
<td>Short</td>
<td>3</td>
</tr>
<tr>
<td>Trains per vent section</td>
<td>1 train per vent section</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>&gt; 1 train per vent section</td>
<td>2,3</td>
</tr>
<tr>
<td>Non-incident tunnel trains</td>
<td>Can drive out</td>
<td>2,3</td>
</tr>
<tr>
<td></td>
<td>Can’t drive out</td>
<td></td>
</tr>
<tr>
<td>Station smoke control</td>
<td>Station platform tenability can be managed by station smoke exhaust</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Station platform tenability CANNOT be managed by station smoke exhaust</td>
<td></td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

Due to the complexity of underground crossovers and the lack of recognized standards there can be a tendency to over specify the requirements for the ventilation system. This paper has discussed several issues, risks, ventilation options and railway characteristics that effect the selection of tunnel ventilation for an underground crossover located adjacent to an underground station. These elements have been assessed qualitatively to give a methodology for understanding how appropriate a given ventilation option is for a given rail network.

6. REFERENCES