Integration of tunnel ventilation and train control systems

M Duckham, K Brown, C F Fleming
SNC-Lavalin, Canada

ABSTRACT

This paper discusses how tunnel ventilation and train control systems can be integrated to achieve high service frequency while maintaining passenger safety on underground metro systems. Increased service frequency is achieved through modern communications-based train control, which can also be exploited for fire-life safety purposes. Assumptions regarding train location and behaviour which are inherent in the tunnel ventilation system design can be encoded as operational rules in the train control system. Appropriate train and ventilation system responses can be predetermined for all potential locations of incident and non-incident trains. In the event of an incident, the programmed response can be presented graphically to the tunnel operator for confirmation. Examples of the integration of train control and tunnel ventilation on a new mass transit rail system are presented.

1 INTRODUCTION

The growth of urban populations presents challenges for transport infrastructure. As cities densify, there is a need to relieve road congestion and to increase the overall capacity of transport routes. These objectives can be met with public mass transit systems. For maximum success, such systems must present a favourable alternative to existing commuting methods, e.g. driving, in terms of journey time, reliability, comfort and safety.

Short journey times and high reliability can be achieved by operating the service along a semi-exclusive or exclusive right of way, such as a fixed guideway. In urban centres, where space on existing surface routes is limited, an exclusive right of way can be provided by a tunnel. Passenger comfort can be improved by providing adequate service capacity, either through long vehicles or high-frequency operation. Recently-developed metro systems in Canada have favoured short trains running at high frequency, which is made possible by Communications-Based Train Control (CBTC).

High-frequency operation of short trains in tunnels presents particular fire-life safety challenges. There is a greater likelihood of multiple trains operating in the same ventilation zone at one time, increasing the potential fire load, evacuation load, and aerodynamic resistance. It also complicates the evacuation strategy. Such situations should either be considered in tunnel ventilation system design, or explicitly prevented from arising by the train control system. Either strategy, or elements of both, can be adopted through integration of tunnel ventilation and train control systems.

Design and operational constraints and risk tolerance tend to be project-specific, and hence the integration of tunnel ventilation and train control systems may not always be warranted. However, tunnel ventilation system designers should give some consideration to the interaction and dependencies of these systems. To highlight some of the issues worth considering, methods of train control are described in the context of fire-life safety, and the integration of ventilation and train control systems on the Eglinton Crosstown Light Rail Transit line in Toronto, Canada (1) is presented.

The emergency management strategy for this metro system is to instruct the incident train to continue to the next station and stop. Station ventilation fans will then be operated in exhaust mode, maintaining a clear evacuation route. The train control system is programmed to support this strategy, and will issue appropriate instructions to non-incident trains (detailed in section 3.3). In the event of an incident arising on a stationary train between stations, the ventilation system will be operated to provide a longitudinal airflow to protect non-incident cars and aid evacuation in the upwind direction. Again, the train control system will issue appropriate commands to non-incident trains to support this strategy.

2 TRAIN CONTROL

2.1 Fixed-block signalling

Fixed-block signalling, where the route is subdivided into fixed sections or ‘blocks’, is a long-established method of train control and is used on most existing metro systems in North America. Safe train separation distances are achieved by allowing only one train in a given block at any instant, and by separating occupied blocks by unoccupied blocks as illustrated in figure 1. The block length is based on the worst-case train stopping distance. This signalling method is not compatible with high-frequency, short headway train operation. Additionally, it poses difficulties for emergency management as the precise locations of incident and non-incident trains are unknown. Automatic train-to-wayside communications are typically limited to route management and signalling, so responses to emergencies must be coordinated manually between train operators and control room staff, with the associated risks of delayed action and miscommunication.

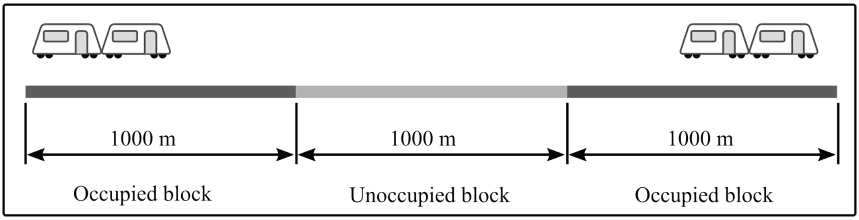

Figure 1: Illustration of a fixed block signalling system.

2.2 Moving-block signalling with transmission-based train control

In moving-block signalling, the occupied and unoccupied blocks move with the trains. This method has been in use since the 1980s, enabled by the development of transmission-based train control, where train position and speed is monitored continuously and controlled automatically. Safe stopping distances are continuously computed based on current train operations and track arrangements/alignments, resulting in variable unoccupied block lengths and higher service frequency, as illustrated in figure 2.

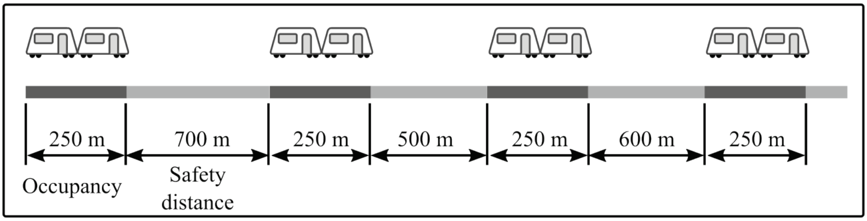

Figure 2: Illustration of moving block signalling, enabling higher frequency train operation.

Train-to-wayside communications are facilitated by induction loops, which can convey information on train position and speed (with high accuracy), vehicle alarm and door statuses as well as signalling instructions. Such information can be automatically provided to control room staff in an emergency, enabling the appropriate response to be determined and implemented quickly. For example, smoke or fire alarm signals can be used to determine the incident car, and a 'door open' signal may indicate if passengers have begun to evacuate from the train. However, cable-based communications systems have some resilience issues. It is difficult to provide redundant communications through the induction loop cable, and the cable is liable to fail quickly in the event of a fire.

2.3 Moving-block signalling with communications-based train control

The capability and resilience of train-to-wayside communications is greatly enhanced with communications-based train control (2). This modern radio-based system allows data transfer at higher rates and wider bandwidths; when allied with fixed location track-bed borne transponders this technology provides improved location accuracy with a higher level of availability. Redundancy of communication is achieved by duplicating train-based equipment and overlapping radio cells along the route, leading to better overall resilience.

The resilience of CBTC makes it a suitable candidate for inclusion with other fire-life safety systems for improved incident response. Useful information can be shared between the train control system and the tunnel ventilation system, to mitigate the risks of high-frequency operation. Unlike conventional fixed-block signalling where emergency management had to be coordinated manually between train operators and control room staff, automated responses can be programmed into CBTC. This can be accomplished not only for the incident train (continue to the next station and stop), but equally important, for the nearby non-incident trains.

One prominent issue is the potential disparity between (implicit) design assumptions and operational realities. Computational models are typically used to verify the ventilation system capacity for particular incident conditions. However rail transit systems often run in a perturbed state (4), due for example to passengers holding doors at platforms, and this can result in ventilation zone occupancy limits being exceeded. In such a situation, the ventilation system may not have the capacity to overcome the additional aerodynamic resistance in the tunnel. Other examples include if an emergency vent is allowed by the signalling system to be obstructed by a stationary train, or if emergency response times are overly optimistic when utilizing a manual system. CBTC can be used to impose constraints on normal train operation, such that ventilation zone occupancy limits and allowable waiting locations are consistent with the tunnel ventilation system design and its supporting computational models.

A further benefit of CBTC is that train behaviour during an incident can be programmed at the design stage, based on the locations and movements of other trains, in line with NFPA 130 requirements (3). Likewise, the optimal ventilation system response can be programmed in advance for each potential emergency scenario (i.e. incident and non-incident train locations). In the event of an incident the appropriate response is automatically determined and presented graphically in the control room for confirmation.

3 CASE STUDY – EGLINTON CROSSTOWN LRT

3.1 System description

The Eglinton Crosstown LRT line runs along and beneath Eglinton Avenue between Mount Dennis and Kennedy Station, as shown in figure 3. The line is 20 km long, with a 10 km twin-bore underground portion between Keele Street and Laird Drive and a maintenance depot adjacent to Mount Dennis station. Fifteen of the stations are underground, and three of these interchange with existing lines.

Figure 3: Overview of the Eglinton Crosstown LRT route.

The railway will feature communications-based train control which is compliant with IEEE 1474 (2). Trains will be operated manually along at-grade sections and automatically in tunnels, where the driver will be responsible for monitoring the line ahead and initiating train departure from platforms.

A high-frequency service will be provided, with two-car trains running at a design headway of 120 s and a top speed of 80 km/h in the tunnels. The platform dwell time is 30 s and inter-station travel times are in the range 80 – 110 s.

Each station features four ventilation shafts which connect to the tunnels near the platform ends. Ventilation fans are bypassed in normal operating conditions, so that tunnels are ventilated via the piston effect of moving trains. In the event of a fire, dampers are switched to connect axial fans to the ventilation shaft flow path. Fans operate in exhaust mode for station fires, and in supply or exhaust mode for tunnel fires to generate a longitudinal flow. Jet fans are used in tunnel sections which are open to grade at one end.

3.2 Ventilation zone occupancy

Discrete ventilation zones are defined throughout the tunnel network, with boundaries at ventilation shafts and at interfaces between single-track and multi-track tunnel sections (e.g. crossovers), as indicated in figure 4. A limit of one train per ventilation zone simplifies the ventilation system response to fire incidents, and is recommended in NFPA 130 (3). Inter-station distances and train headways on the Eglinton Line are such that the single-train limit is theoretically possible. However line service disruptions, such as passengers holding doors at platform, are commonplace in rapid transit systems (4). With a single-train limit, delays will propagate to following trains along the line, exacerbating the disruption and reducing the appeal of the overall service. Given the 120 s headway and a travel time of up to 110 s, a train schedule would show that two trains would never co-exist in the same ventilation zone. However, the operational realities of the aforementioned train operations would lead to two trains in a zone somewhere on the system on a regular basis. In fact, unless restrictions are put in place in the signalling system, multiple delays over the course of the day could lead to more than two trains in a ventilation zone.

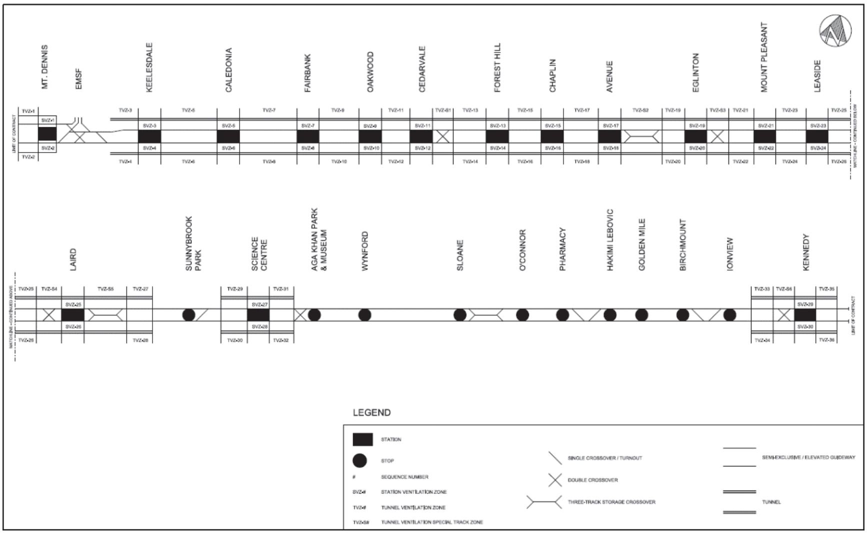

Figure 4: Tunnel and station ventilation zones on the Eglinton Crosstown LRT.

A limit of two trains per ventilation zone is applied on the Eglinton Line, to reduce the propagation of delays and enable a more acceptable level of service for commuters. Nevertheless, at any given moment there will likely only be one train in most ventilation zones.

In the event of an incident where there are two trains in a ventilation zone, the non-incident train is removed where possible, in line with the NFPA 130 recommendation for this scenario (3). However this response is not always possible, due to the presence of trains in adjacent ventilation zones or other operational limitations. For example, an operator must be present in the leading cab to move the train, which precludes the prompt reversal of a train from an incident ventilation zone.

Hence the ventilation system is designed to achieve critical velocity with two trains present in a ventilation zone. Additionally, rules are implemented in the train control system to prevent trains stopping where they would obstruct emergency vents.

3.3 System integration

The fire detection, tunnel ventilation and train control systems on the Eglinton Crosstown LRT interface via the SCADA system, such that relevant data is automatically shared between systems (figure 5). For example, the location of activated fire and smoke alarms on board a train are processed by the train control system and the appropriate pre-defined control instruction is delivered to each train (e.g. apply emergency brakes, stop at next station, skip next station). The SCADA system processes the same incident train signals, as well as location signals from non-incident trains, to determine the appropriate ventilation mode and propagates the emergency command to the tunnel ventilation system. This and other relevant information is presented graphically in the control room for confirmation.

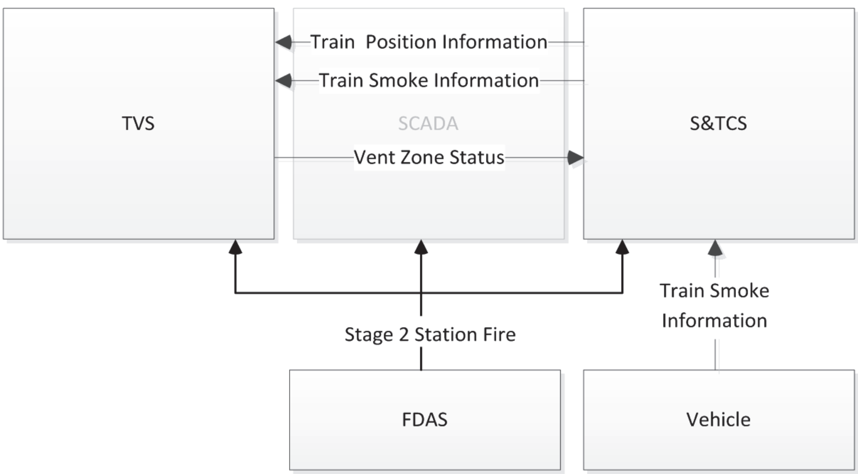

Figure 5: Illustration of data sharing between the tunnel ventilation system (TVS), signal and train control system (S&TCS), fire detection and alarm system (FDAS) and SCADA.

Some examples of responses to particular emergency scenarios are presented to illustrate the system design.

3.3.1 Incident on a moving train

If fire or smoke is detected on board a moving train, the tunnel ventilation fans at the next station will be operated in exhaust mode (figure 6) and the train control system will provide the following instructions:

- The incident train will stop at the next station and its doors will open.
- Any train at the non-incident platform will be instructed to depart.
- Any train approaching the incident station in either direction will brake.
- Trains will be held stationary at stations preceding the incident station along the approaching routes.

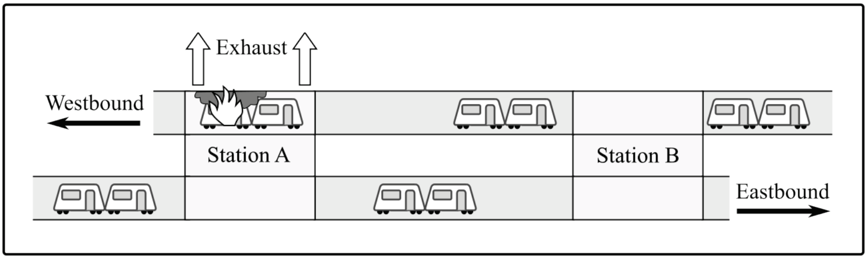

Figure 6: Ventilation system response for an incident on a moving train, showing the incident train stopped at the next station.

3.3.2 Incident on a stationary train in a tunnel

At any given instant, most tunnel ventilation zones will contain only a single train, as the design headway is 120 s and inter-station travel times are 80 – 110 s. If an incident train is immobile in a tunnel, for example due to a failure of the pantograph and/or OCS caused by the fire, the ventilation system will be operated to generate a longitudinal airflow in the tunnel.

The flow direction is determined based on the location of the incident car (indicated by the onboard smoke alarm) so that the non-incident car is protected, as shown in figure 7.

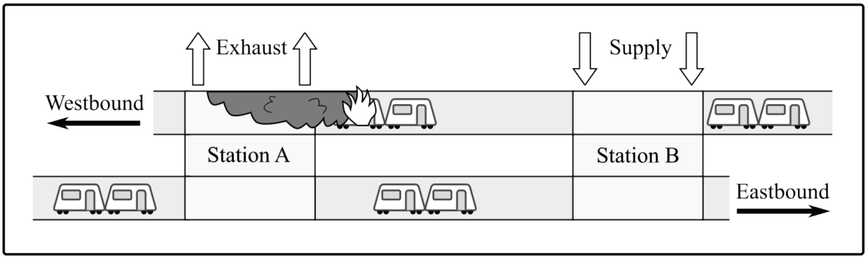

Figure 7: Ventilation system response to protect the non-incident car.

The train control system will issue the following instructions:

- Trains approaching the incident ventilation zone will apply full service brakes or emergency brakes if necessary.
- The station ahead of the train will be closed, i.e. trains will be instructed to depart.
- Trains will be held stationary at stations preceding the incident station along the approaching routes.

3.3.3 Incident with two stationary trains in a tunnel

The train control system allows up to two trains in a tunnel ventilation zone, to reduce delay propagation and to allow trains to recover lost time. In the event that two stationary trains occupy a ventilation zone and an incident is detected on board one of them, the train control system applies the following rules in addition to those in section 3.3.2:

- Trains ahead of the incident train in the same ventilation zone will be instructed to continue out of that ventilation zone.

- Trains behind the incident train in the same ventilation zone will apply emergency brakes.

If non-incident trains successfully exit the ventilation zone, leaving only a single train, the ventilation strategy is the same as in section 3.3.2. Otherwise, if two trains remain, the ventilation system response depends on the location of the incident car.

If the incident occurs on a station-side car, as indicated in figure 8, the ventilation system will be operated to protect the non-incident car and the non-incident train.

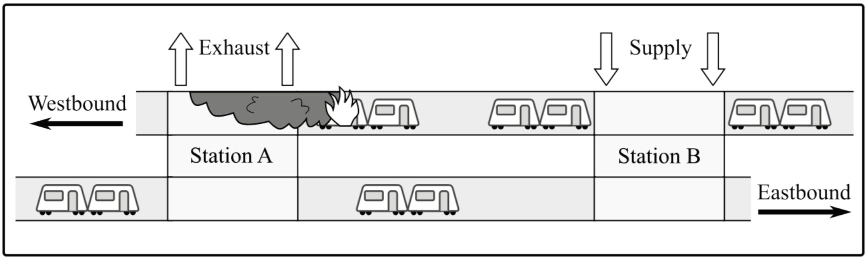

Figure 8: Ventilation system response to protect the non-incident car and the non-incident train.

A dilemma arises if a fire occurs on the tunnel-side car, as shown in figure 9. In this scenario, the protection of passengers who are not intimate with the initial development of the fire is prioritised, and the ventilation system operates in the direction of the incident train. Note that this is the default ventilation scenario for this situation, however, the control room operator may choose to take a different course of action at the time of emergency depending on the information and options available to them. Further design and operational considerations should be taken if more than two trains per ventilation zone are allowed, scheduled or otherwise.

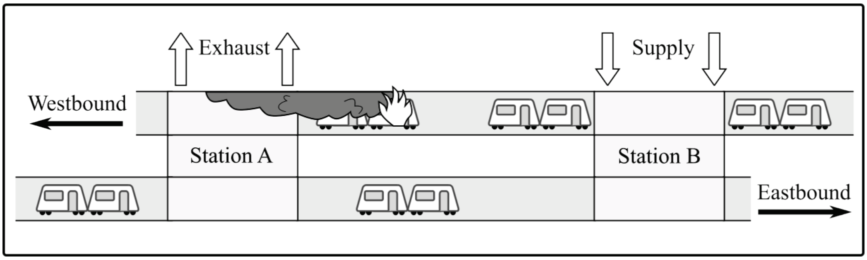

Figure 9: Ventilation system response to protect the non-incident train.

3.3.4 Other scenarios

A comprehensive range of potential incident scenarios have been considered for the coordination of ventilation and train control systems on Eglinton Crosstown LRT, including cases where the incident train is located across a ventilation zone boundary, near a tunnel portal, within special trackwork areas, or in a maintenance facility.

It is important to note that while many automated responses have been programmed into the train control system, the train operator or the control room staff are always capable of overriding these if they feel it is safer to do so given exact the circumstances of the event.

The train control system is also utilized in congested conditions. As the exact locations and speeds of trains are known, the control centre will be alerted if a train has been standing in a tunnel longer than a certain allowable period. Control room staff can then activate a congestion ventilation mode to manage tunnel air temperatures in the affected ventilation zone.

4 CONCLUSION

High-frequency metro services pose difficulties for fire-life safety, such as the potential for multiple trains occupying a single ventilation section, or stationary trains obstructing emergency vents. However, the technology that enables high-frequency operation – communications-based train control – can also be utilized to improve the emergency response. Explicit operational restrictions can be implemented at the design stage, for example regarding ventilation zone occupancy and train stopping locations.

Additionally, the appropriate behaviour for incident and non-incident trains can be predefined and coordinated with the ventilation system response for all potential train and fire locations. In the event of an emergency, the appropriate train and ventilation system response can be presented graphically to the operator for confirmation, reducing communication and decision time.

While project constraints, risk level and risk tolerance might be such that the integration of ventilation and train control systems is unwarranted, the system interactions described in this paper should be given some consideration by tunnel ventilation system designers.

REFERENCES

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