Impact of Tunnel Ventilation on Tunnel Fixed Fire Suppression System

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ABSTRACT

Recently there have been major fires in a number of European tunnels that required reevaluation of road tunnel fire loads. This showed that tunnel safety requires applying a fixed fire suppression system in addition to a tunnel ventilation system. This introduces a new challenge when designing tunnel safety systems. The type of ventilation system influences the type of sprinkler system and the sprinkler system design impacts the ventilation system performance. The design is also affected by the sequence of system activation. For example, sprinkler activation during calm airflow will differ from activation during fully developed turbulent air flow, which may carry away sprinkler droplets. On the other hand, the ventilation system may experience significant resistance due to water curtains created by the sprinklers. This paper addresses the types of tunnel ventilation systems, types of sprinkler systems, their influences and new design challenges to achieve a final goal, which is a safe tenable environment for evacuation during a fire emergency.

INTRODUCTION

PIARC, NFPA and several European countries are rethinking fixed fire suppression application for tunnels. Before the Alpine tunnel fire disasters, Japan and Australia were the only two countries to require and use sprinkler systems in road tunnels. It is noted that sprinklers were installed in several other tunnels in other places in the world, including the USA. However, those installations were driven by specific requirements and jurisdictions. Fixed Fire Suppression Systems have been successfully used for more than 40 years in Japan's congested urban road tunnels and, more recently, in all of Australia's congested urban tunnels. Today, over 100 tunnels are equipped with an active fire protection system. This paper uses the terms "sprinkler system", "active fire protection" and "fixed fire suppression system" to mean Water-based Fixed Fire Suppression System (FFSS).

NFPA 502 recognizes the benefits of the FFSS for road tunnels, but was concerned with the reliability of fire detection technology, further visibility reduction and the impact of the FFSS on the effectiveness of tunnel ventilation. For an active fire protection system to be effective, it is essential that fires be quickly and accurately detected. The latest developments in tunnel FFSS applications were possible due to achievements in fire detection technology.

It is recognized that active fire protection systems can limit the size and growth of a fire and prevent the fire from spreading. It could also protect tunnel lining, possibly reducing the amount of passive structural fire protection and making significant construction and operation savings. A fire involving several heavy goods vehicles would not close the tunnel protected with a FFSS for a lengthy period.

Tunnel ventilation systems are still the main tunnel fire life safety systems to control smoke and provide a tenable environment for evacuation. Table 1 illustrates that there is a number of common benefits from ventilation and FFSS, which can support each other in cooling down the tunnel environment and supporting fire fighting procedures. However, there are

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several expected conflicts noted between the two systems, such as fire growth, fire spread, visibility and tenability. An in-depth analysis of the impact of tunnel ventilation on the tunnel's water based fixed fire suppression systems, as well as the analysis of the impact of fire suppression on tunnel ventilation, is required.

Table 1. Expectations from Tunnel Ventilation and Fixed Fire Suppression Systems

Tunnel Ventilation		Fixed Fire Suppression	
Expected benefits	**Expected Concerns**	**Expected benefits**	**Expected Concerns**
Controls smoke and other gases	Increases the fire growth	Slow down the fire growth, reduces fire size and overall smoke production	Reduce visibility and thus negatively impact the tenable environment
Provides tenable environment for evacuation, including visibility	Supports spreading fire further impacting other vehicles	Prevent spreading of fire further impacting other vehicles	Destroy stratification of hot air and smoke and may disrupt ventilation system operation
Cools down the tunnel environment		Cool down the tunnel environment	Increased humidity and its impact on tenability and fans
Supports fire fighting procedures		Support fire fighting procedures	Produce toxic smoke due to incomplete combustion
		Protect assets	Become slippery Hazard for evacuation

TYPES OF TUNNEL VENTILATION AND THEIR IMPACT ON FIXED FIRE SUPPRESSION SYSTEMS

There are two major types of ventilation for tunnel applications: longitudinal and transverse. Longitudinal system is defined by the longitudinal airflow movement along the tunnel initiated either by natural factors (wind, stack effect, piston effect of vehicles) or by fans (portal fans, shaft fans or jet fans along the tunnel).

Transverse ventilation is defined by the transverse airflow movement in the tunnel. Transverse ventilation systems feature the uniform collection and/or distribution of air throughout the length of the tunnel roadway and can be of the full transverse or semi-transverse type. In addition, semi-transverse systems can be of the supply or exhaust type.

Single Point Extraction (SPE) systems are conceptually similar to transverse exhaust ventilation systems. However, SPE systems utilize a limited number of large extraction openings that provide localized exhaust during a fire emergency, which supplements the performance of the transverse exhaust ventilation system at the fire site. Single Point Extraction systems can be supported by longitudinal ventilation systems, such as jet fan systems, to prevent the spread of smoke and hot gases along the tunnel and directing them to a SPE opening.

Longitudinal Ventilation

Impact on fixed fire suppression system largely depends on the type of tunnel ventilation and on longitudinal airflow along the tunnel. The only feasible way to evacuate smoke with longitudinal ventilation is by pushing it through the tunnel toward the portal at air velocities not less than "critical velocity" in order to prevent it from backlayering. NFPA 502 and other standards allow for a maximum air velocity in a tunnel of 12 m/s (2200 fpm). Ventilation systems are designed for significantly smaller critical air velocities, but in combination with wind, other natural factors, and traffic pattern, the resultant air velocities may be that high.

What will high air velocities do to the performance of the fixed fire suppression system? At high longitudinal air velocities light water mist will most likely be blown away, while heavy deluge water droplets will be displaced. As of today, water mist systems have been tested at significantly lower longitudinal air velocities not exceeding 5 m/s. The deluge system, using much heavier (large) water droplets, may be considered with high longitudinal air velocities once it is proven that it provides similar or a better level of safety.

Does the fixed fire suppression system add any benefits to the longitudinal ventilation system, especially in the evacuation phase? While it takes about 30 seconds to activate a wet sprinkler system, it may take 3 to 4 minutes to fully implement the ventilation mode due to inertia and electrical loads. It means that the sprinkler system can be activated in a relatively calm environment before ventilation is at full speed. This allows for a faster wet FFSS system to be activated over the incidence zone. However, once ventilation mode is in full effect, the sprinkler activation zones should be switched to account for a blow-away effect from the longitudinal ventilation. This could require deactivation of one downstream zone and activation of an upstream zone under full system pressure. The middle zone would stay activated throughout the process.

System activation, by opening the emergency control valve and deactivation by closing the valve, is a critical component of controlling the deluge system for optimum effectiveness. Recent technological advances have made it possible to activate and deactivate the deluge system with one simple ball valve and/or a remotely controlled solenoid valve. Valve operation utilizes standpipe water pressure fed to the back side of the valve. Under no circumstances should there be complete deactivation of the deluge sprinkler system until either the fire is extinguished or managed by the fire department.

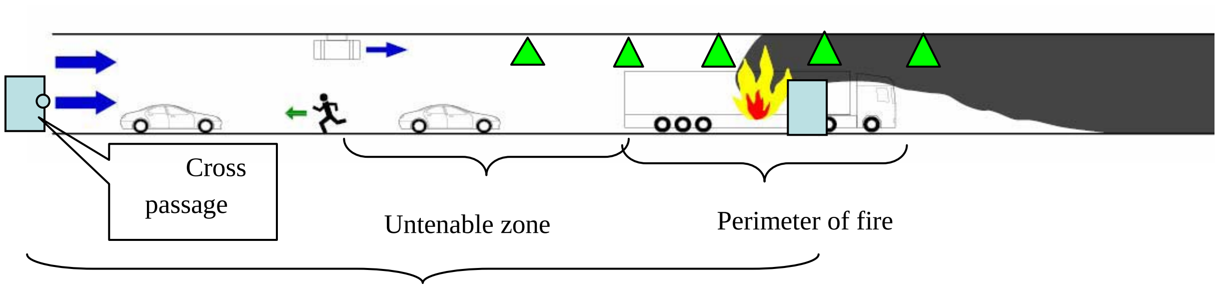

Figure 1 Longitudinal Ventilation with Fixed Fire Suppression System

Fast, reliable fire detection and prompt activation of fixed fire suppression and ventilation systems are of vital importance in order to obtain benefits from the combined operation of FFSS and longitudinal ventilation systems. With the fixed fire suppression system, longitudinal airflow may need to be selected to ensure an appropriate droplet spread and mass flow performance for given water pressures. Otherwise, appropriate fixed fire suppression zones need to be activated depending on longitudinal airflow.

The ventilation system is also affected by sprinkler operation. Water curtains create a significant resistance to longitudinal ventilation needed for preventing smoke backlayering. However, the critical velocity requirement may also be reduced due to the reduced fire heat release rate. The temperature tenability requirements can be met with less ventilation; however, smoke toxicity and air humidity are a concern. The performance of tunnel ventilation fans should be evaluated considering lower temperatures, water curtains and additional mass of moisture.

Transverse Ventilation

Transverse ventilation uses both supply and exhaust ducts served by a series of fans usually housed in a ventilation building or structure. Exhaust openings are often located at the ceiling level relying on stratification to extract smoke and hot gases. However, there are systems with sidewall exhaust air openings, which depend less on stratification, but more on pressure created by the fans.

A semi-transverse supply system will most likely not be used for removing smoke to avoid its spread along the tunnel. The only exception could be if the fire were located close to the exit portal. In this case, the semi-transverse system will operate effectively, just as with longitudinal blowing smoke away through the exit portal.

The traditional way to extract smoke with semi-transverse exhaust systems is to use small ceiling openings distributed at short intervals throughout the tunnel. The balance of airflow is made up via the tunnel portals.

Single Point Extraction (SPE) uses large openings with remotely controlled dampers directly above the incidence with suitable extraction ports. This system works best in conjunction with jet fans (see Figure 2) or portal (Saccardo) nozzles to localize smoke around openings and to prevent smoke driven by natural factors (such as wind and tunnel grade) from spreading along the tunnel. To maintain smoke stratification, a low speed longitudinal air velocity is usually required to push smoke to one side of the fire.

Longitudinal air velocities for full transverse, semi-transverse exhaust, and SPE systems are relatively small and the displacement of water droplets due to ventilation is diminished. However, water droplets will most likely destroy stratification and lower the efficiency of these systems.

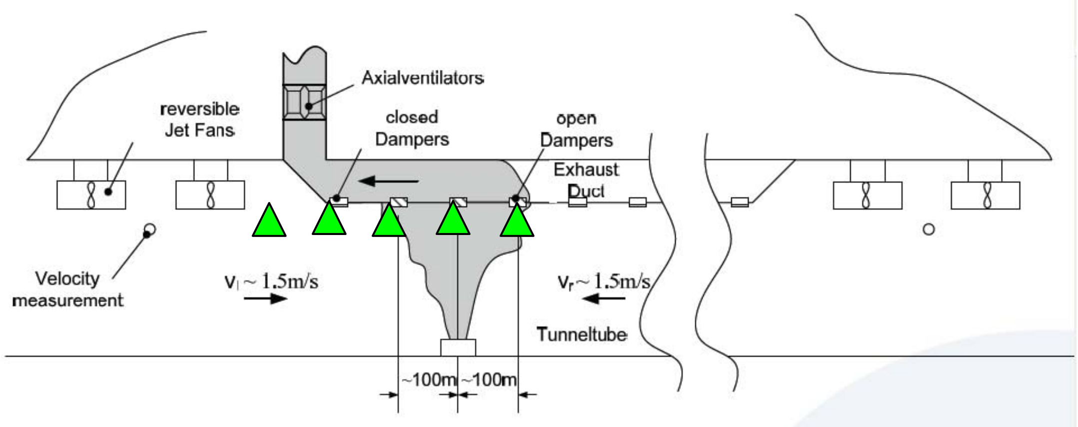

Figure 2 Single Point Extractions with Fixed Fire Suppression System

Since longitudinal air velocities are relatively low with transverse and single point extraction systems, any type of tunnel fixed fire suppression system can be considered. The water mist system may be beneficial since it produces less stratification disturbance, provides a better cooling effect and is somewhat safer for the mechanical and electrical equipment. However, reduction of visibility in the path of evacuation due to the loss of smoke and hot gases stratification has to be considered. Does the fixed fire suppression system bring additional benefits? Which fire suppression zones shall be activated first? Would the delay in sprinkler activation be beneficial? Are there other means of fixed fire protection system activation to mitigate its possible negative impact on ventilation, such as water shield mitigation system (WSMS)? While an engineer has to find answers to these questions, it seems obvious that FFSS systems are beneficial for emergency and rescue services.

Table 2. Analysis of Fixed Fire Suppression System benefits to SPE

Activation to support Evacuation (early activation)		**Activation to support First Responders (activation after evacuation)**		**Activation to support Property Protection**	
Advantages	**Consideration**	**Advantages**	**Consideration**	**Advantages**	**Consideration**
Temperature reduction	Loss of stratification, loss of visibility and toxicity	Temperature reduction	Ventilation mode may need to be changed to longitudinal	Beneficial on early stage	Possible post-cooling spalling needs to be considered
Radiation reduction	Impact on fans and needed flow rate	Radiation reduction			

Table 2 provides a sample analysis of additional benefits and consideration to be addressed when analyzing a fixed fire suppression system in addition to a single point extraction ventilation system. Similar analysis can be provided for any type of ventilation system. The main benefit of controlling the fire growth and reducing the heat release rate (and thus the overall smoke production rate reduction) can be achieved with a well designed, reliable and quick fire detection system with rapid activation before the fire gets too large.

TYPES OF WATER BASED FIRE SUPPRESSION SYSTEMS

There are many types of water based fire suppression systems but only a few that are found to be applicable to the tunnel environment. Restrictions, such as open portals, natural ventilation and huge tunnel volumes, prevent the practical application of most suppression systems. The two types of water based fire suppression systems found to present the most benefits in the tunnel environment are intelligent water mist and deluge sprinklers.

While a few automatic fire sprinkler systems have been installed in tunnels, most of them are deluge type. A deluge system has a network of open nozzles at the roof of the tunnel, divided into zones, typically 30 m (100 ft), which is based on the length of a heavy goods vehicle. When there is a fire, a deluge valve is opened in the zone above the fire and in the zone on either side of it. Water is sprayed from all the nozzles in the activated zones.

The water mist system, which gained popularity due to water conservation and saving tunnel space, has been installed in several European tunnels. A water mist system is similar in zoning and operation to the deluge system with the exception that it utilizes different kinds of water mist (density, droplet sizes, pressure and so forth). Its comparison with the deluge system is shown in Table 3.

Table 3. Comparison of Water Mist and Deluge Systems Components

System	Pumps	Piping	System components	Droplets	Coverage	Advantages	Disadvantages
Water Mist	Yes – high pressure 100 + bar	Stainless steel high pressure tubing	Special nozzles Control panel High pressure valves	50 (0.002 in) to 300 (0.01 in) microns	Varies depending on head selection and design fire size	Uses less water Smaller pipe sizes; Compact valve box; Effective at reducing heat; Components hold up to the harsh tunnel environment	Highly effected by high air velocities; High pressure pumps; Specialized personnel
Deluge	As needed	Standard black iron fire pipe	Deluge sprinkler heads; UL Listed Deluge valve assembly with butterfly valve, tamper switch and trim; (PRV) pressure reducing valves	1mm (0.04 in)	Varies depending on design fire size	Conventional systems easily maintained; Compact valve box design available; Well suited to the harsh tunnel environment.	Substantial Water demand; Large distribution pipes; PRVs effected by high air velocities

Deluge and water mist systems have been selected over automatic sprinkler systems because of several reasons. First, heat from a fire does not stay over the fire, but travels along the tunnel. This requires a fire detection and suppression system that can adequately deal with a fire that has heat and smoke dispersed far away from its source. Second, the tunnel fire could rapidly develop a great deal of heat over a large area enveloping more sprinklers than the water supply can handle. Third, automatic sprinklers lack flexibility.

FIXED FIRE SUPPRESSION SYSTEM ACTIVATION TIME AS A FUNCTION OF TYPE OF VENTILATION

There is a variety of controls available for the FFSS: to fully integrate FFSS with ventilation, operate them separately, fully automate them, automate them with manual override and manually operate them with auto override. However, each of these options must be carefully evaluated. Different tunnels may require different approaches. Some approaches may consider automatic activation with or without time delay and override. Others may consider activation by an operator or by the Fire Department only. It all depends on the objectives of the system.

Typically, a project establishes a time-of-tenabilty criterion for fire life safety system design. Figure 3 provides an example of such a curve, which shows fire curve (fire development), self rescue and fire life safety (FLS) activation relative to fire development. This example illustrates that evacuation will start while fire grows and well before ventilation mode can be fully activated. The only means to get fire growth under control is to activate a wet sprinkler system before ventilation. Ventilation should remove smoke and toxic gases once activated. Considering that the amount of water required for fire suppression is directly related to the size of the fire, it becomes critical to activate the deluge water supply no later than the design fire heat release rate achieved on the curve.

SELF RESCUE	FLS SYSTEMS ACTIVATION
1. Make a decision to evacuate	1. Detection Time
2. Disembark the bus	2. Operator Reaction Time (alarm)
3. Walk away from the fire effected zone	3. FFSS Systems Activation
4. Reach cross passage	4. Ventilation (All Fans) Activated
	5. Ventilation Mode in Full Operation

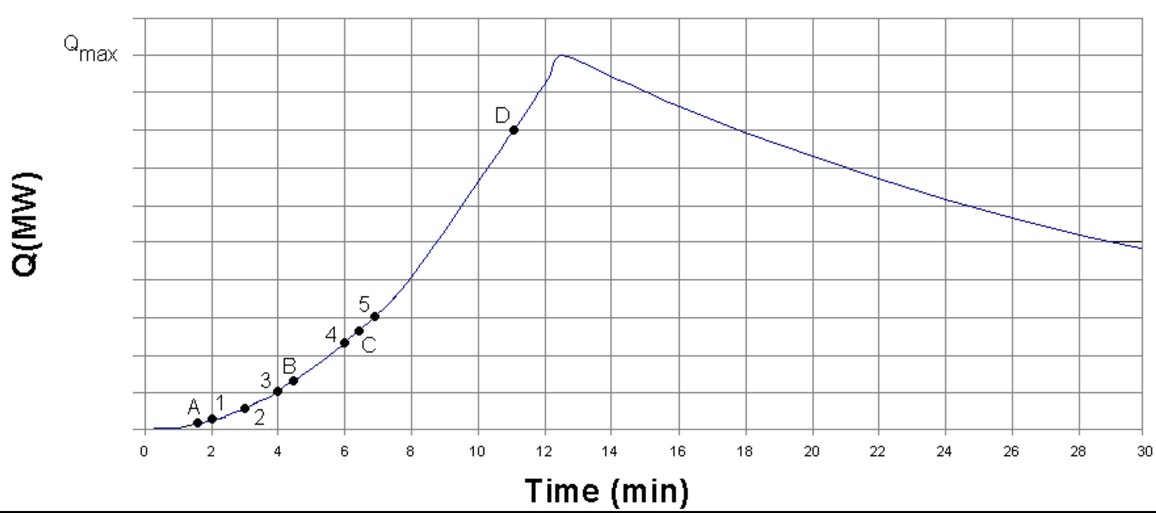

Figure 3 Example of project established time-of-tenability curve

A delay in activation may produce a huge volume of high temperature steam as dangerous as the combustion products.

If all ignition sources cannot be extinguished and the site uniformly cooled below a safe temperature, the fire may reignite, perhaps explosively, when the sprinklers are shut off. Such an explosion happened during the Ofenegg tunnel Tests (1965) causing extensive damage to the test setups and injuring three technicians. Figure 4 illustrates the effect of FFSS suppression on Heat Release Rate. With timely activation of suppression system, the heat release rate reduces. With delayed activation, the fire overwhelms and the suppression system is not effective, as shown in Figure 4.

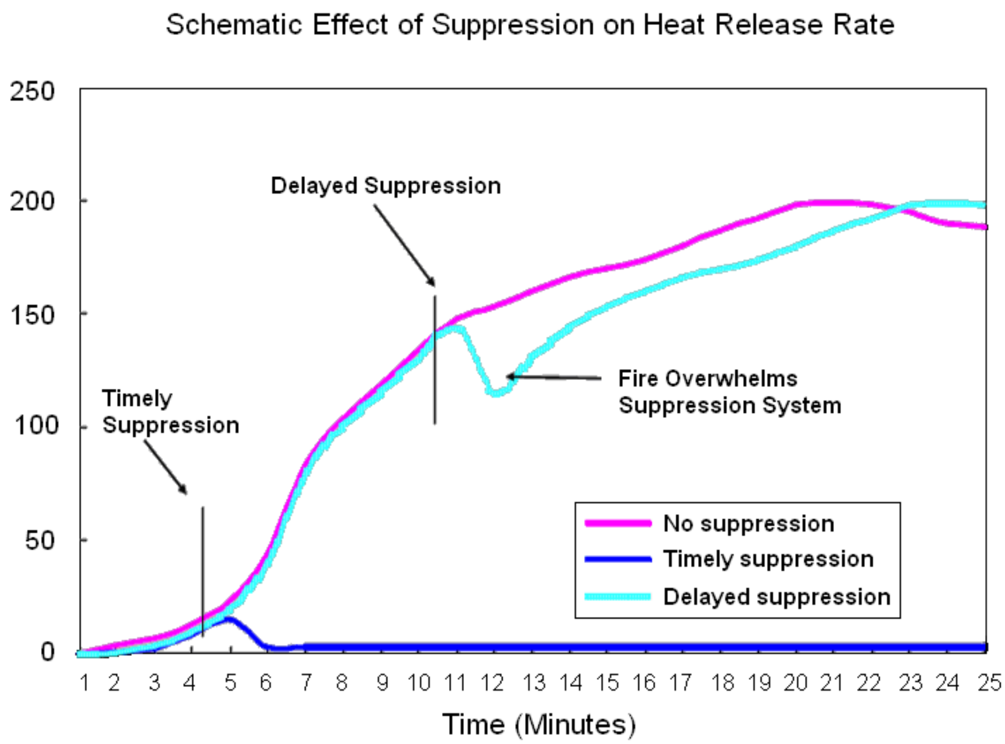

Figure 4 Schematic Effect of Suppression on Heat Release Rate

Automatic activation of the sprinklers by active detectors may need to be delayed since even a light spray could startle unaware drivers and cause the roadway to be slippery. Accidental activation of the system with cause unknown, which happened in Boston, is unacceptable.

Post-cooling concrete spalling needs to be considered when deciding on sprinkler activation. It occurs after the fire is out, after cooling down or maybe even during extinguishing. This type of spalling was observed with concrete types containing calcareous aggregate. It appears that the application of a fixed fire suppression system on the very early stage of a fire development can actually help cool down the fire and surface and protect the structure, while a delay can initiate a post-cooling spalling. This leads to an understanding of the importance of a reliable fire detection system and activation of the fixed fire suppression system at the very early stage of fire development in order to cool down the tunnel's walls. By limiting the development of a fire, its duration can be limited, resulting in the tunnel structure enduring less harsh conditions.

With the longitudinal ventilation system, it seems reasonable to activate both systems simultaneously. As a result, the wet fixed fire suppression system will initially start before the longitudinal ventilation reaches full speed. This allows the sprinkler system to discharge water in a low air velocity environment, thus protecting people and structures by taking control of a fire at an early stage of its growth. Once the ventilation reaches full speed, the sprinkler zones may need to be revisited and either switched or additional activation zones will be required to account for ventilation. The question is: if the sprinkler is activated early enough, can ventilation be reduced or eliminated and what will be the impact on smoke production?

With the transverse ventilation system using ceiling exhaust, the sequence of activations may differ. Destruction of the smoke layer, worsening of visibility, and potential generation of hot steam need to be considered. The Japanese approach for the transverse system may be reasonable, which allows for a minimum of a 3-minute delay before the sprinkler activation, so that people can leave the sprinkler zones. However, sprinkler activation delay may be dangerous for the tunnel structure and can lead to fire spread and growth. It may also require a greater water supply, due to a larger fire size at the time of activation. This needs to be studied further.

CONCLUSIONS

The type of ventilation system influences the type of sprinkler system and the sprinkler system design impacts the ventilation system performance. Some of the challenges faced with considering ventilation and FFSS in the tunnel are:

- Selection of the type of FFSS depends on the type of tunnel ventilation system.
- Wet fixed fire suppression systems can be activated before ventilation and can control fire growth rate, fire size, and the overall smoke production rate at an early stage of fire development.
- Activation time of FFSS may differ depending on the type of ventilation.
- For longitudinal ventilation, the sprinkler zones may need to be switched or additional zones may be required once ventilation mode is in full speed.
- With transverse ventilation, a short system activation delay may need to be considered.
- Delay with the FFSS activation will require additional water supply because of the larger fire size at the time of activation.
- Extended delay with FFSS may result in its inability to control fire, in structural damages and possible explosion. Reliable automatic fire detection system is essential.

The undesirable consequences of FFSS activation, such as smoke destratification, increased humidity and decreased visibility, are hopefully outweighed by its other positive outcomes of fire growth rate control, containment of fire spread and reduced temperatures. The questions which need additional investigations are whether the fixed fire suppression system can replace other tunnel fire life safety systems, such as ventilation and passive protection systems, or whether the size and requirements for such systems can be reduced?

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