Risk Management of Long and Deep Tunnels - The European Experience

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INTRODUCTION AND OBJECTIVES

The operational safety of long and very long rail tunnels represents a key issue in all development stages, including design, construction, commissioning and operation. The spectrum of potential threats is very broad and challenging. These issues can only be mastered by means of a proper combination of a number of safety measures at various levels.

This paper focuses on the specific safety issues and the extremely challenging conditions characterizing very long and deep tunnels. They include a significantly increased risk during operation that the incident train cannot exit the tunnel by its own means, long self-rescue and rescue distances, the presence of a number of trains, possibly mixed traffic as well as significant thermal issues.

Amberg Engineering is strongly involved in the design and construction of most long and very long rail tunnels in Europe, including in particular the Gotthard Base Tunnel (GBT), Lyon-Turin Base Tunnel (LTF) and the Brenner Base Tunnel (BBT). The combined experience arising from these tunnels forms an invaluable body of expertise, which is summarized in this paper. The focus is on shared issues with practical relevant examples and project-specific solutions.

Special attention will be devoted to the 57 km long Gotthard Base Tunnel, which will be operational by mid-2016 and will be the longest infrastructure tunnel worldwide.

VERY LONG TUNNELS IN EUROPE

Overview

From the point of view of safety, tunnels in excess of about 20 km exhibit a significantly increased risk that incident trains could stop within the tunnel. This is related to the European Technical Specifications for Interoperability (TSI) on rolling stock, to be discussed in the chapter on rescue stations. This paper will specifically focus on the following longest tunnels in construction or operation, listed in Table 1.

Table 1. Longest rail tunnels in Europe

Tunnel	Length	Country	Commissioning
Gotthard Base Tunnel	56.7 km	Switzerland	2016
Brenner Base Tunnel	55 km	Austria / Italy	under construction (2026)
Lyon-Turin Ferroviaire	57.5 km	France / Italy	under construction (ev. 2028)
Lötschberg Base Tunnel	34.6 km	Switzerland	2007
Eurotunnel	49.7 km	France / Great Britain	1994

Gotthard Base Tunnel

The 56.7 km long tunnel system consists of two single-track tunnels. The two rail tunnels are about 40 m apart and joined every 312 meters by connecting galleries. Two double crossovers allow trains to change from one tunnel to the other in the multifunction stations at Sedrun and Faido. An emergency station is located in each multifunctional station, allowing trains to stop in an emergency. From there passengers can escape and be evacuated. Should an incident occur, smoke is extracted from the affected tunnel and fresh air blown into the emergency stop station through the side tunnels and connecting galleries. A slight overpressure is sufficient to prevent smoke from entering the escape route to the unaffected tunnel. The distance between the emergency stations and to the portals is just below 20 km. If a train stops before it reaches an emergency station, passengers can use the connecting galleries to escape to the other railway tunnel. Firefighter intervention is based on special firefighting trains.

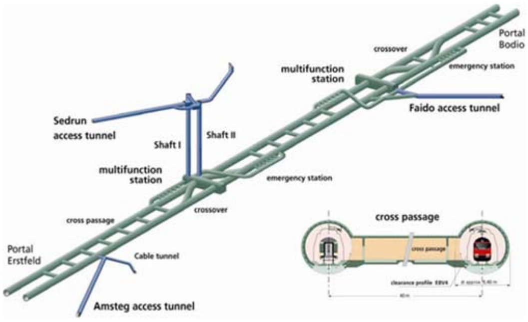

Figure 1. Overview Gotthard Base Tunnel (GBT15)

Figure 2. Emergency Station GBT (GBT15)

Brenner Base Tunnel

The Brenner base tunnel will be built with two single track tunnels with an inter-distance of 70 meters on a length of 55 km. Every 333 m there is a cross passage between the two main tunnels. On most of the tunnel length an exploratory tunnel will be built. This third tube serves as drainage, service and exploratory tunnel but not as security gallery. Emergency evacuation will take place in one of the two emergency stations or through the cross passages into the second tube.

Figure 3. Overview Brenner Base Tunnel (BBT15)

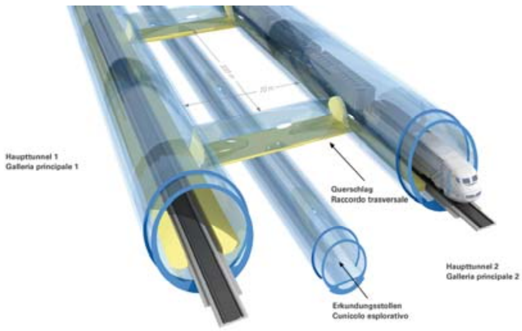

Figure 4. Cross Section Brenner Base Tunnel (BBT15)

Lyon-Turin Ferroviaire

The base tunnel will consist of two 57 kilometer long single track tunnels with cross passages every 333 meters. There will be three emergency stations in La Praz, Modane and Maddalena. In case of an emergency the trains can stop in an emergency station and the passengers and train crew can escape in a safe room between the two tunnels. Firefighter can access this room on a separate level to intervene on a burning train and look after injured people. The passengers will then be evacuated by train through the second tunnel. Firefighter have also the possibility for putting their vehicle on the track and enter the tunnel if the fire is in-between the emergency stations. Passengers can escape through the cross passages into the second tube if a train has to stop outside of the emergency station. Two cross overs allow the trains to change tube in Modane and two overpassing tracks in Modane allow high speed trains to overpass slower freight trains.

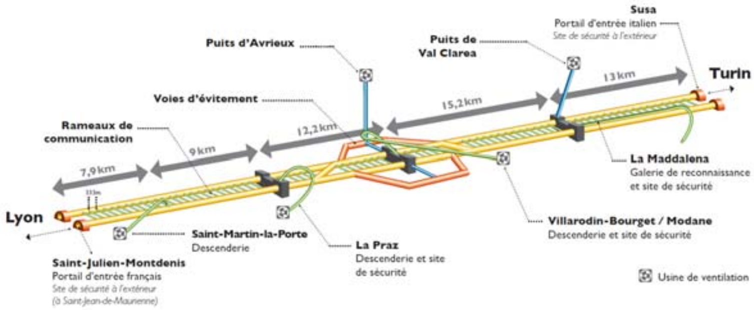

Figure 5. Overview Lyon - Turin Base Tunnel (LTF15)

Lötschberg Base Tunnel

The Lötschberg Base tunnel system has twin single-track tubes with a length of 34.6 km. For economic reasons, only one of the tubes was fully equipped while the second one was left largely as a shell. The two tubes are connected by transverse tunnels at 333-metre intervals, meaning that each tunnel can be used for the evacuation of the other. In the northern section where only one tube was excavated, a parallel emergency tunnel guaranties the safe escape. There is one emergency station in Ferden and intervention areas outside the portals. If the incident train cannot leave the tunnel, an enforced stop can be done in Mitholz service station or at any point in the tunnel. Firefighter intervention is done similar to the Gotthard Base Tunnel based on special firefighting trains located at the portals of the tunnel.

Figure 6. Overview Lötschberg Base Tunnel (LBT15)

Figure 7. Firefighting train (LBT15)

Eurotunnel

The 50 kilometer long Eurotunnel is also based on two single track tunnels. It is the only long railway tunnel in Europe with an additional emergency gallery. The three tunnels are connected every 375 meters by cross passages. This tunnel does not have emergency stations as the other long railway tunnels. If a train needs to stop in the tunnel, passengers can escape into the safe service gallery. They will then be brought out of the tunnel by an evacuation train through the second tube. Firefighters use special vehicles running through the service gallery. Two double cross over at one third and two thirds of the tunnel allow the trains to cross from one tunnel to the other.

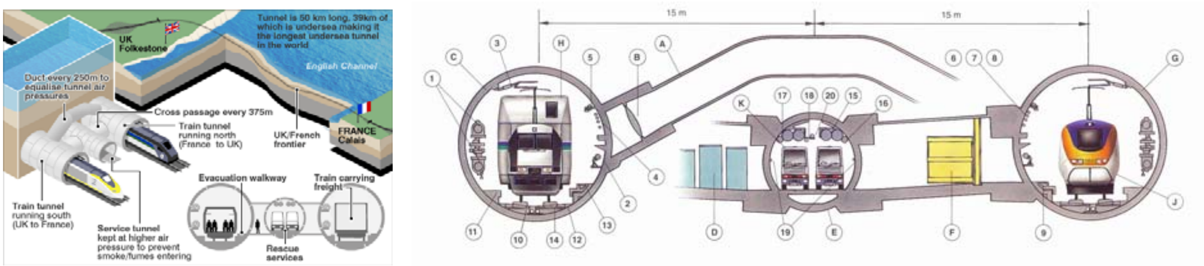

Figure 8. Overview Eurotunnel (left Eurotunnel15, right Wikipedia)

SPECIFIC SAFETY ISSUES OF VERY LONG TUNNELS

There are many tunnel-specific risks, including derailment, collision, explosion, propagation of dangerous gases and many more. Rescue and person evacuation in case of “cold” incidents (i.e. without fire) certainly represents a very serious issue, because of the long intervention times and extreme logistic problems. Nevertheless, the main safety issue for very long tunnels is fire. Self-rescue and intervention can be extremely difficult, particularly taking into account the large number of people characterizing modern long-distance passenger trains (typically 1,000 to 1,500 persons). This frequently leads to very large time intervals, where escaping persons are exposed to smoke and noxious combustion products.

Because of these difficulties, operating procedures in most cases require that burning trains leave the tunnel and stop at the nearest favorable outside location. Trains manufactured and tested according to the European TSI are certified for covering, according to the highest certification level, at least 20 km in case of fire. The risk that burning trains stop within the tunnel significantly increases for tunnels in excess of 20 km. Additionally to lateral walkways and emergency exits, emergency or rescue stations represent the most common solution.

Several trains transit in very long tunnels at any time. Thus, a number of trains could be affected in case of incidents or accidents, particularly in case of fire. Frequently very long tunnels are operated with mixed traffic. Several passenger and good trains (frequently including dangerous goods) typically transit through the tunnel at any time. The Gotthard Base tunnel is a typical example. Besides the regular schedule for person transportation, with speeds up to 220 km/h, as many as 260 freight trains will be able to pass through the tunnel every day, with speeds ranging from 100 to 160 km/h. Different speeds lead to variable distances between the trains and add to the safety challenges. All trains must leave the tunnel before the emergency services can access the incident or accident site, unless a dedicated safety tunnel is available. This mostly results in long to very long self-rescue and intervention times. Suitable measures for protection of the escaping persons are required.

Another specific issue with important implications for tunnel safety is the high thermal load resulting from high coverage. As an example, rock temperatures close to 50°C were measured during the excavation of the Gotthard base tunnel.

SELECTION OF THE APPROPRIATE TUNNEL SYSTEM

The following tunnel systems could be envisaged for very long tunnels, including:

- Single-tube, double-track systems with rescue tunnel

- Double-tube (e.g. Gotthard, Brenner and LTF Base Tunnels (e.g. Figure 1, 2 and Figure 3, 4)
- Double-tube with emergency tunnel (e.g. Eurotunnel and Gibraltar, e.g. Figure 8)
- Mixed systems (e.g. Lötschberg Base Tunnel).

Double-track systems do generally not allow for an adequate level of safety and are excluded. Because of trains crossing, the number of trains potentially involved in a fire dramatically increases. Moreover, intervention through the fire tunnel tube is most cases extremely difficult and dangerous. Intervention should use the safety tunnel, where the users from the incident train escape. Further a rather large diameter of the rescue tunnel would be required.

Double-tube systems separate the two traffic directions and allow for an excellent level of flexibility in terms of train and smoke management. They represent by far the most common solution. The inclusion of a safety tunnel is certainly very useful from the point of view of safety and availability but is generally rejected because of its high cost. It can be very appealing for exploration purposes in case of critical geological issues. Safety tunnels are used for self-rescue and for intervention. They are also very useful as service tunnels in normal operating conditions. They significantly increase the flexibility for routine maintenance operation and allow for rapid intervention in case of technical disturbances. Safety tunnels can therefore significantly add to tunnel availability and reduce maintenance cost.

The decision process can be illustrated based on the Gotthard Base Tunnel, Figure 9.

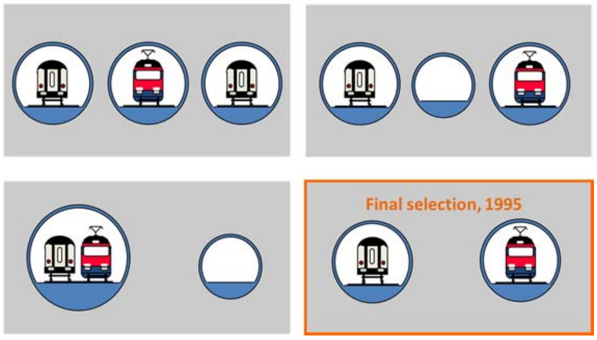

Figure 9. Choice of tunnel system for Gotthard Base Tunnel

RESCUE STATIONS

Emergency or rescue stations are commonly realized in tunnels exceeding about 20 km of length. The rationale lies in the European classification of trains (TSI 1303/2014 and its previous version TSI 2008/163/EC) with respect to fire protection and running characteristics in case of fire. Two main train categories are defined:

- Category A passenger rolling stock (including passenger locomotives) for operation on lines, where the distance between firefighting points or the length of tunnels does not exceed 5 km.
- Category B passenger rolling stock (including passenger locomotives) for operation in all tunnels, irrespective of the length of the tunnels

Depending on the rolling stock allowed for, the maximum distance from the portals to a firefighting point and between firefighting points is limited to 20 km (only category B allowed) or 5 km (general case).

Rescue stations (“firefighting points” according to the terminology used in the TSI) are primarily needed for safety reasons, but are very useful for construction purposes and for hosting a variety of tunnel equipment. They must allow the proper handling of a large number of persons (state-of-the art long-distance trains typically carry up to 1,000 to 1,500 persons). From the safety point of view , the key requirements of rescue stations are:

- Optimum conditions for self-rescue
- Optimum conditions for intervention
- Possibility of evacuating the tunnel users in case of emergency
- Technical measures for mitigation, including a proper level of smoke management.

The elements composing a rescue station are the emergency station where the burning train stops, where passengers escape and rescue intervention can start. From the stations' platforms an adequate number of connections to a safe areas are needed, from where the users can be evacuated. The facilities and equipment for intervention and person evacuation can be concentrated in these points as well.

The measures for supporting self-rescue include:

- Reduced spacing between emergency exits
- Sufficiently wide walkways and doors
- Good lighting
- Optical guidance and signalization
- User communication.

In the safety stations the mitigating measures generally include at least a fire detection, ventilation and lighting. Further communication to the users by loudspeakers and video surveillance is common. FFFS (Fixed Fire Fighting Systems) are frequently installed as well. If properly designed and installed, they can effectively reduce fire development, thus supporting firefighting and reducing damages to the infrastructure.

Ventilation measures shall support self-rescue and intervention, but shall above all protect the escaped users until they can be evacuated from the tunnel (typically of the order of 1 to 2 hours).

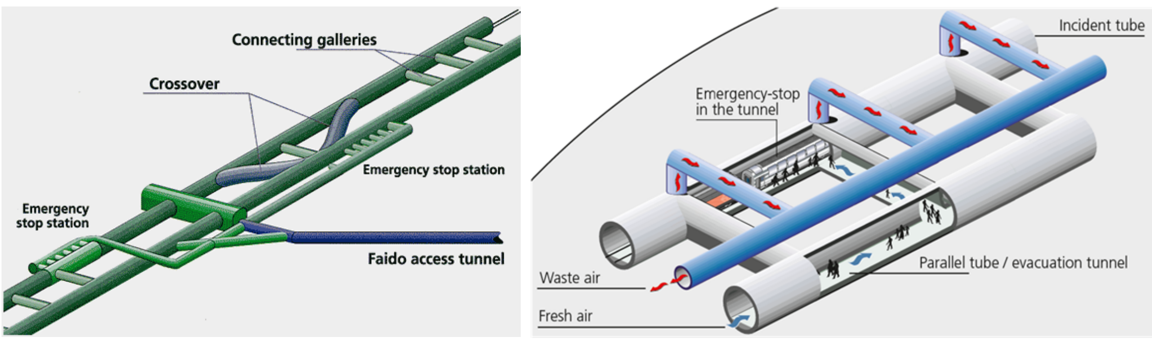

Figure 10. Faido rescue station in the Gotthard Base Tunnel

The Gotthard Base Tunnel has two rescue stations at Faido and Sedrun, Figure 1 and Figure 10. The particularity is that the emergency stops, where burning trains shall stop, can be reached before passing the crossover. This greatly reduces any residual risk of derailment in case of emergency with partly damaged trains. The persons then escape through the cross connections into a protected parallel gallery, from where they can reach the rescue station belonging to the non-incident tube. From there evacuation to the outside is carried out by train.

The safety strategy adopted for LTF is slightly different and is based on one main safety station (Modane), two safety points (La Praz et la Maddalena) and an emergency access point (Saint-Martin-la-Porte), Figure 11.

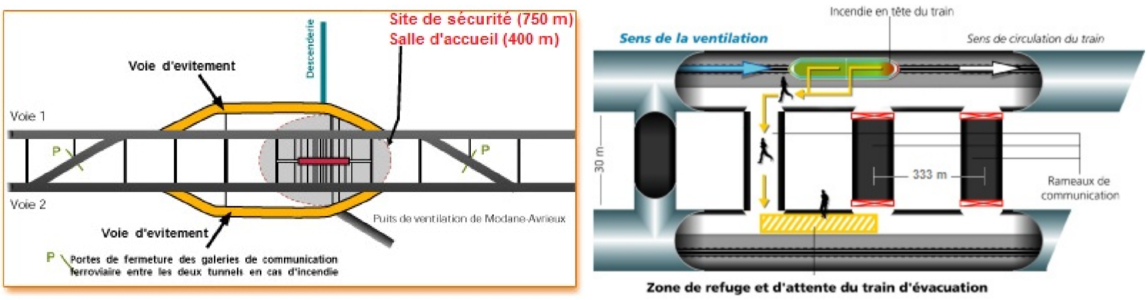

Figure 11. Rescue stations in the Lyon-Turin Base Tunnel (Left: safety station at Modane; Right: safety point)

FURTHER FACILITIES FOR SELF-RESCUE

It cannot be excluded, that trains stop outside a rescue station. This can occur in particular in case of fires occurring, as a consequence of accidents such as derailments or in case of loss of electric power in the tunnel (e.g. because of a broken catenary). Thus, appropriate self-rescue facilities shall be provided also in case of a train emergency stop outside a rescue station. This typically consists of:

- Lateral walkways on one or both sides of the tunnel
- Cross connections protected through fire-protection doors and a dedicated ventilation system
- Lighting, signaling, communication facilities etc.

The minimum requirements in terms of spacing of emergency exits according to TSI and Swiss national requirements are as follows:

- Double-tube systems: Maximum 500 m
- Single-tube systems: Maximum 1,000 m (to the surface).

Analysis and experience shows, that these values are clearly inadequate for the long Alpine tunnels, which all have adopted distances between cross connections in the range of 300-350 m. This value was largely dictated by the investigations carried out for the Gotthard Base Tunnel, where an interval of 312 m was finally selected.

Figure 12. Fire-protection doors in the Gotthard Base Tunnel

A key element for protecting cross sections and recue stations are fire-protection doors. The level of thermal protection must obviously be selected based on the whole tunnel safety concept. Further aspects are sometimes neglected. One of them is the proper functionality in case of fire, which requires a high level of insensitivity towards pressure differences. Sliding doors are common for long rail tunnels, see e.g. Figure 12. Severe requirements in terms of mechanical stability can arise also in normal operating conditions, because of pressure fluctuations generated by train movement. Design pressure differences reach ±10,000 Pa in the Gotthard Base Tunnel. The testing procedure was therefore extremely challenging.

VENTILATION

All long tunnels require a very powerful ventilation system covering all relevant operating conditions, including in particular normal operation, maintenance and emergency operation. Only a short overview is provided herein. A comprehensive review was provided by Bettelini and Rigert (2014).

Overview

Ventilation is generally not needed in normal operating conditions. Three noteworthy exceptions shall be mentioned but not treated further:

- Ventilation in case of maintenance
- Ventilation for reducing the temperature critical parts of the tunnel
- Ventilation of technical rooms

It should be noted that the former elements of tunnel ventilation can have a very relevant impact on emergency ventilation, since part of the equipment is the same. Safety ventilation must account for two distinct situations: Fire in a rescue station and fire at any location in the tunnel.

Fire in a rescue station

The essential components of the fire-ventilation system of a rescue station are:

- Smoke extraction form the incident tunnel, where the burning train is stopped
- Fresh-air injection into the incident tube through the emergency exits, for preventing smoke penetration into secured areas and into the safe tube
- Fresh-air supply to the place, where the users are waiting for evacuation

Their combined action provides best-possible conditions for self-rescue and intervention.

Fire at any location in the tunnel

In case of a train stop at any location inside the tunnel, self-rescue and intervention must occur through the safe tunnel tube through the cross connections. The essential functions of fire ventilation in case of train stop outside of the emergency station are:

- Mastering the longitudinal air velocity in the incident tunnel, for limiting as much as possible smoke propagation and preventing the loss of natural stratification of the hot combustion products (very large longitudinal air flows almost invariably occur in very long rail tunnels, because of large thermal effects, severe mesoscale pressure differences and train motion)
- Protecting cross connections against smoke penetration
- Creating an overpressure in the safe tube for preventing smoke penetration also in case of open fire-protection doors on both sides of a cross connection.

The Gotthard Base Tunnel

Ventilation systems are frequently exceptionally demanding and challenging. This can be illustrated by means of a few key data from the Gotthard Base Tunnel:

- 2 fresh-air fans, each with wheel diameter 2.8 m, motor power 1.5 MW, peak flowrate 235 m^3/s, pressure 4,300 Pa in each rescue station
- 2 exhaust fans, each with wheel diameter 2.8 m, motor power 2.4 MW, peak flowrate 275 m^3/s, pressure 6,400 Pa in each rescue station
- 56 thermal cameras and 9.6 km thermal detector for fire detection and localization within the rescue station
- 354 fans and 573 dampers for ventilating the cross connections

INTERVENTION

There are different philosophies on the intervention concepts in long railway tunnels, depending on the operator, the firefighters and the local regulations. There are three basic strategies:

- Rescue trains
- Road-rail vehicles
- Conventional road vehicles (mostly specific vehicles for the specific tunnel)

These different strategies have some influence on the tunnel layout as access must be guaranteed if a road connected system is used. The rescue train will use the empty rail tunnel in front of the accidental train to enter the tunnel from the portal. This firefighter train will not need any additional infrastructure. The road-rail vehicle will drive to the closest access point in an emergency station with the possibility to access the track there. To do so specific platforms must be built to allow the access of the vehicle to the rail track. Finally, the conventional road vehicle will use a separate tunnel to get to the intervention point. Therefore a separate service / emergency gallery is needed. All solutions have advantages and disadvantages and the choice depends on the country's infrastructure, the operator's philosophy, the accessibility of the tunnel, the tunnel layout based on the construction method and the geological requirements (e.g. investigation gallery to be used as separate emergency tunnel?) or other factors.

But there is one common fact to all the different strategies: the rescue teams will never arrive on time at a burning train. Due to the long access distance the firefighting teams will not be on spot within the time the passengers have to evacuate the train to guarantee their safety. Therefore all safety philosophies are based on self-rescue. People need to have the possibility to quickly escape from the danger zone on their own and to reach a safe place where they can wait for rescue. These safe places can be created in a parallel tunnel or a cross passage by providing fire-safe separation doors / walls and preventing smoke penetration by means of a slight overpressure in the safe zone and underpressure in the incident tunnel. The passengers will then be evacuated by train, as only trains have the capacity to evacuate these large amount of persons.

Firefighters will arrive on site to rescue wounded persons and to contain the fire and try to minimize the impact of the fire on the tunnel structure. To fight the fire they will either bring their water supply, if a rescue train is used, or have hydrants in the tunnel.

INCIDENT MANAGEMENT IN THE GOTTHARD BASE TUNNEL

If a train catches fire while running through the Gotthard Base Tunnel, it will first try to exit the tunnel. If this is not possible, the train will stop in an emergency station. As soon as the train issues an alarm, the emergency ventilation will start creating overpressure in the safe zones. The emergency station will be prepared remotely by opening the escape doors and putting the light on. The operator can communicate with the passengers via audio system and video cameras are available. A powerful exhaust ventilation will evacuate the smoke to guarantee best-possible self-rescue conditions. The incident train will reach the emergency station and all occupants will enter the escape gallery. As soon as the people reach the escape gallery, they are (temporarily) in safety. The maximum distance they need to walk from the train to the nearest escape door is 30 meters as the doors are spaced 60 meters apart.

Other trains will be stopped before entering the tunnel and the trains following the incident train will reverse out of the tunnel leaving the tunnels empty for rescue. Passengers will then be directed through the safety gallery connecting both emergency stations towards the emergency station in the other tunnel.

The emergency stations in the Gotthard Base Tunnel are not just opposite to each other, as an important design principle was that the incident train shall not cross a switch before entering the emergency station. So the emergency stations were placed on both ends of the double cross overs. This philosophy is not followed by the new long base tunnels as the risk of a crossing of a switch is accepted or the tunnels have no cross overs. Once the passengers arrive in the other emergency station an evacuation train will be there to take them out of the tunnel. In case the train doesn't make it to the emergency station, it will stop anywhere along the tunnel and people will escape through the cross passages to the second tube. As soon as they pass the first cross passage door they are in a secure place and can wait for a train in the second tube to bring them out of the tunnel.

CONCLUSIONS AND OUTLOOK

A significant number of very long tunnels have been commissioned, are under commissioning or under construction. Safety issues are crucial and have a large impact on design. The intervention philosophy and the safety elements must be integrated in the earliest design stages as they are mostly driving the design choices. A wise design can combine most of the required space for safety and technical installations with the space for installations during the construction phase. To do so, the key space consuming elements of the safety concept (escape route, rescue access and ventilation) must be defined in the first project stage to allow a perfect correlation with the construction requirements.

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