AERODYNAMICS, VENTILATION AND TUNNEL SAFETY FOR HIGH SPEED RAIL TUNNELS

Rudolf Bopp, Gruner AG, Basel - Switzerland
Bernd Hagenah, Gruner GmbH, Vienna - Austria

Abstract

With increasing train speed the pressure wave, which is generated at the entry of a train in a tunnel and which propagates at the speed of sound through the tunnel, as well as the train induced airflows, become evermore important. Tunnel aerodynamics must therefore be considered in the design of new high speed tunnels. This paper gives in a first part an overview of the relevant aerodynamic topics which have to be confronted during the design process:

- Pressure loads on equipment and doors inside the tunnel
- TSI safety criterion
- Tunnel cross section, train sealing and pressure comfort
- Sonic boom and possible countermeasures

In the second part of the paper the most important aspects related to ventilation and tunnel safety are presented. Special attention is given to long double bore tunnels with two parallel tunnel tubes connected by cross passages.

1 Introduction

Modern high speed railway lines are often characterised by more and longer tunnels. With increasing train velocity the aerodynamic effects due to high pressure fluctuations and high airspeed in the tunnel have a direct influence on the design of the tunnel (tunnel cross section, pressure relief shafts, portal hoods etc.). Aerodynamic phenomena have thus to be taken into account in the design phase of a new high speed line or in the case where an existing line is upgraded to be operated with higher train velocities.

Especially in longer tunnels the aspects of tunnel safety must also be considered. Escape routes and access for emergency services have to be provided. An optimum selection of infrastructural, technical and organisational safety measures must be taken into account. In very long tunnels even underground emergency stations with smoke exhaust systems may become necessary.

The paper gives an overview over the most important aerodynamic (chapter 2) and safety (chapter 3) aspects which have to be addressed in the design of railway tunnels and which may have significant consequences on the tunnel system.

2 Tunnel Aerodynamics

2.1 Pressure variations in high speed train tunnels

2.1.1 Phenomena

Pressure fluctuations in high-speed rail tunnels occur due to train induced pressure waves and by passing trains. Pressure waves - compression or expansion waves - are generated when:

- trains enter or exit tunnels
- trains pass cross-sectional variations
- trains pass openings to the opposite bore (for single track double bore tunnels)
- trains pass shafts or other openings to the outside

Pressure waves in tunnels travel with the speed of sound. If compression waves hit portals they are reflected as expansion waves and vice versa.

In addition, trains cause pressure fluctuations in a tunnel due to a sharp pressure drop when a train nose passes and due to the pressure decrease along the train (see figure 1).

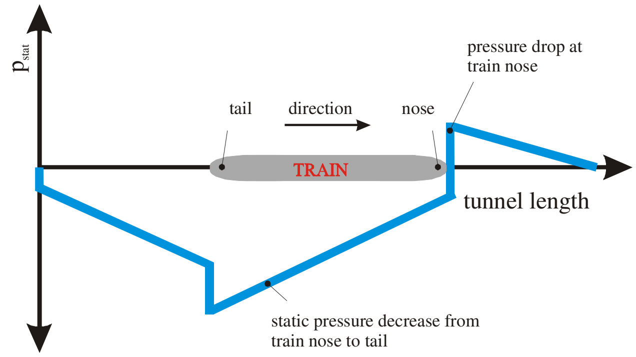

Figure 1: Pressure profile in a tunnel showing the pressure drop at the train nose and pressure decrease along the train

The superposition of pressure waves, reflections and the static pressure decrease along the train (from nose to tail) as well as the pressure drop at the trains nose will cause rather complex pressure situations in the tunnel and hence inside the train. Figure 2 shows the pressure signature at an arbitrary point in the tunnel for a simplified situation without any pressure wave reflection.

Additionally, any track gradient will cause changes of atmospheric pressure for passengers as well. E.g. a height difference of 100 m will cause atmospheric pressure differences of approximately 1.2 kPa.

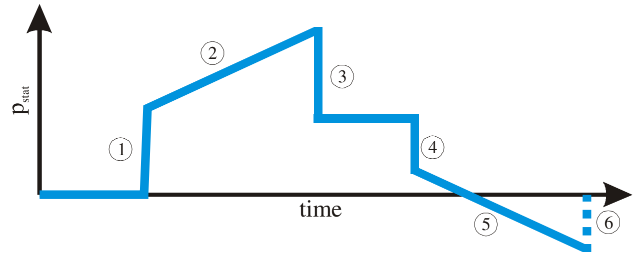

Figure 2: Pressure variation at a selected point inside a tunnel due to a train entrance (see table 1 for breakdown of events)

Table 1: Numbers denoted in Figure 2 and explanation of pressure variation origin

No.	**Origin pressure variation**
①	Entrance of the train nose leads to a sudden compression wave with a pressure rise.
②	Pressure increase due to air friction on the train surface.
③	Entrance of the train tail generates an expansion wave. The pressure signal (1), (2) and (3) travels through the tunnel with the speed of sound and will be reflected at the exit portal. Reflections are not shown.
④	Sharp pressure drop due to the passage of the train nose.
⑤	Pressure decrease from nose to tail while the train passes, almost inverse of signal (2).
⑥	After the passage of the train tail the pressure will return to the prevailing atmospheric pressure (might take some time).

2.1.2 Assessment of pressure variations

First rough estimations of pressure variations in tunnels can be done with simplified semi-analytical approaches [3], [4]. However, more sophisticated situations involving successive trains or reflections from passing trains etc. are too complex for analytical approaches. On the other hand, complex pressure variations can be predicted by modern 1d numerical simulation tools. This is not very surprising since the physical dimension of tunnels and trains are more or less one dimensional. However, experience and knowledge is needed for accurate consideration of several phenomena, such as the impact of air friction, train nose and tail shape, cross-sectional changes of tunnels, etc. [6].

The use of powerful simulation tools is especially recommended if different design parameters should be taken into account, such as pressure waves, traction power, pressure comfort, etc.

2.1.3 Magnitude of pressure variations

The magnitude of pressure variations depends on several parameters. The most important ones are the train speed, the blockage ratio (A_{Tunnel} / A_{Train}) and the tunnel length.

Normally, the highest pressure amplitudes are generated at the train entrance. Due to air friction and damping, pressure waves will decrease while travelling through tunnels. But, for relatively short tunnels, it is important to take reflected pressure waves into account. Hence, the magnitudes of pressure variations differ for different tunnel lengths. The 'critical tunnel length' is defined as the length with the highest train induced pressure variations, caused by the superposition of reflected pressure waves and the static pressure decrease at the train tail. The investigation of the critical tunnel length gives for single train runs conservative amplitudes of pressure variations. Different critical tunnel lengths are shown in table 2.

Table 2: Critical tunnel length for different train speeds and train lengths

train length [m] train speed [km/h]	200 200	400 250	400 350
critical tunnel length [m]	2178	2886	1572

The impact of pressure variations in tunnels is of high importance for the electronic and mechanical equipment (cabinets, jet fans, cable ducts, doors, etc.). As mentioned train induced pressure waves travel through tunnels at the speed of sound. Hence, objects hit by the pressure wave will be passed within a fraction of a second. However, passing pressure waves might act on enclosed volumes within the tunnel system (e.g. closed cable ducts, closed cross-passages, etc.). Specifically doors and dampers between the tunnel bore and an adjacent volume (technical room, cross-passage, ventilation duct, etc.) need to be able to withstand the aerodynamic loads. It is evident, that small objects, like hectometre signs are not affected since the extension in the propagation direction is about 2 mm (no volume) and hence, the pressure equalisation between both sides will happen within approx. 10^{-6} s. Pressure loads generated by passing trains will have the same effect on closed volumes, doors, etc.

If it is possible that several trains move through the tunnel system simultaneously, two major aspects have to be taken into account: (1) Due to the superposition principle, much higher pressure variations may occur.

(2) Aerodynamic pressure loads will act on the rolling stock itself. This will cause forces across train surfaces and act on windows, doors, junctions, etc.

2.2 Air flows in high speed train tunnels

2.2.1 Phenomena

Trains entering and passing through tunnels accelerate the internal air column (piston effect). The air speed obtained is rather low (approximately 3-8 m/s). On the other hand, passing trains will generate high air speed (gusts) in the annulus between train and tunnel. Close to the train, the air speed might be 30 % higher than the train speed [9]. Gusts will act on air flow exposed equipment like signs, loud-speakers, jet-fans, catenaries-system, hand-rails, cable ducts, cameras, etc.

2.2.2 Assessment of air flows

Airflow loads on equipment are of high importance for the dimensioning and the selection of the electro mechanical equipment. A rough estimation for the dynamic pressure of the train induced air flow is given by the Deutsche Bahn guideline [2], which has to be applied for new rail tunnel projects in Germany. However, for different rolling stock, cross-sectional areas of the rolling stock, train speed, cross-sectional areas of tunnels, track design, passenger- / freight-traffic, etc. the choice and application of these guidelines has to be analysed carefully.

1d numerical tools are able to predict the piston effect excellently. However, if detailed analysis or knowledge of the air flow around trains is needed (e.g. critical loads on exposed objects) 3d simulation tools have to be used.

It should be mentioned, that air flow due to the piston effect will cause air inflow at the entrance portal and outflow at the exit portal of single track tunnels. Hence, the air exchange will have an impact on the tunnel climate, especially in the portal regions.

2.3 TSI pressure criterion and pressure comfort

2.3.1 Basics

The pressure variations in the tunnel are transmitted by openings from the exterior of a train to the interior. Hence, the pressure level inside a train can not be constant and will vary. Pressure variations within a certain time interval (few seconds) are relevant to the passenger pressure comfort and health [5]. High pressure variations inside a car body may lead to discomfort and in extreme cases injure passengers or staff.

TSI health criterion:
The European specification for interoperability of high speed trains defines that pressure variations must not exceed pressure variations of 10 kPa (peak to peak) within the entire passage through a tunnel - in any situation [14]. This value is mandatory and valid even for a complete failure of the train sealing (e.g. broken window) and crossing high speed trains. This strict criterion is called the TSI health criterion.

Pressure comfort:
For lower pressure variations the travel and pressure comfort are strongly related to individual perception. Hence, different national rules and guidelines were developed over the last 20 years. Maximum pressure variations (peak to peak) which should not be exceeded during a certain time interval are usually defined [6].

- The most popular pressure criteria are defined within the UIC-Code 660 [16], which is originally addressed to rolling stock manufacturers.
- The UIC-Code 779-11 [17], which is addressed to the tunnel design (civil-engineering), gives contradictory recommendations.

Table 3: Pressure comfort criteria (maximum pressure variation within a certain time interval)

time interval **criteria**	**1 s**	**3 s**	**4 s**	**10 s**	**60 s**
UIC 660	< 0.5 kPa	< 0.8 kPa	-	< 1.0 kPa	< 2.0 kPa
UIC 779	< 1.0 kPa	-	< 1.6 kPa	< 2.0 kPa	-
SBB Rail 2000 (project specific,)	-	-	< 1.5 kPa	-	-
Tunel de Guadarrama (project specific)	-	-	< 2.5 kPa	-	-

However, passengers may feel bad or sick even though pressure comfort criteria are met. Generally the comfort of passengers does not specifically depend on the pressure variations, other important aspects are:

- distraction / entertainment (nice landscape, interesting discussions, etc.)
- noise (rail, aerodynamic or loud passengers, etc.)
- vibrations
- state of health or age of passengers
- frequency and duration of tunnel passages

After several years of experience working with the UIC-660 pressure comfort criteria it comes out that specifically the long time criterion (Δp_{max} in 60 s < 2 kPa) is very difficult to satisfy. The main reason is the development of rather long double bore single track tunnels with typically small free cross-sectional areas ($A_{Tunnel} \approx 40 - 50\ m^2$). The constant pressure decrease along the train during the tunnel passage leads to a significant pressure-step at the exit portal. Indeed several studies concerning pressure comfort are underway in Europe with the aim to understand more about this phenomenon and the impact on passengers.

However, since the topology of countries is important for the track design (Netherlands with no mountains compared to Austria within the Alps), it is evident that pressure comfort criteria will stay a national or project specific aspect.

2.3.2 Train sealing

The most used countermeasure for high pressure comfort on high-speed lines with tunnels is the use of sealed trains. Normally pressure variations outside the train (exterior to the train surface) will be transferred to the train interior by openings. Hence, the pressure between exterior and interior of the train will be equalised. Large openings will lead to faster equalisation than small ones. Sealed trains with minimised openings lead to slow pressure equalisation.

Typically sealed trains have excellently sealed body junctions, good door sealing, closed cable lead-through, etc. The train sealing quality may vary with the aging and the usage of the rolling stock. The most important impact factors are:

- the frequency of usage
- the route of usage (tunnels, quality of tracks, vibration, twisting of coach etc.)
- the exposition to sunlight (uv-radiation on sealing) or other aggressive environment
- quality of the original materials and the standard of manufacturing (poor or brilliant finishing, etc.)
- quality and frequency of maintenance.

It is convenient to describe the pressure development inside the train ($p_{interior}$) on the basis of the external pressure ($p_{exterior}$) and a pressure sealing coefficient τ. The τ - value gives the time in seconds in which the initial pressure differences at t = 0 s is decreased to 36.8 % of the initial difference.

Figure 3 shows the pressure evolution inside a train ($p_{interior}$) for two different train sealing coefficients: τ = 0.5 and 5.0 s for a generic situation were the pressure difference of 100 % is present at τ = 0 s (step function). It can be seen that in the sealed train (τ = 5.0 s) the pressure change is much slower, leading to smaller values of maximum pressure changes in a given time interval. Typical train sealing coefficients for different train types are listed in table 4.

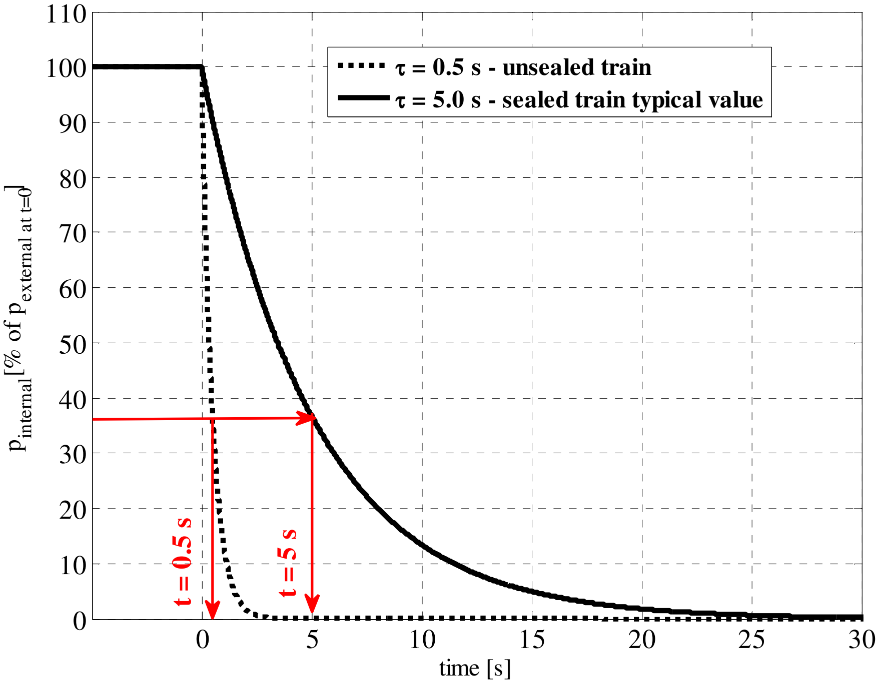

Figure 3: Pressure evolution inside a train for two different sealing values (τ = 0.5 and 5 s)

Table 4: Typical τ - values for different train types [5]

Train type	**Pressure sealing coefficient**
unsealed train (e.g. regional transport)	τ < 0.5 s
poorly sealed train (e.g. Eurocity)	0.5 s < τ < 6 s
well sealed train (e.g. ICE1, TGV)	6 s < τ < 15 s
excellently sealed train (e.g. ICE 3, AGV)	τ > 15 s

2.3.3 Other measures to reduce pressure fluctuations

Instead of using sealed trains to provide high pressure comfort, it is possible to take other measures into account [19]. The most important measures are listed in table 5 below:

Table 5: Measures to reduce pressure variations in tunnels

Measure	Description	Effect	Advantage	Drawback
operative	Reduced train speed	Reduced amplitudes of pressure waves	No construction costs.	Unreasonable solution on high speed lines
	No succeeding or crossing trains	No superposition	No construction costs	Unreasonable solution on high speed lines
civil	Portal Design (e.g. trumpet shape)	Lower pressure wave amplitude at entrance portal	-	Expensive, might be disadvantageous for pressure comfort while leaving the tunnel
	Openings between tunnel bores or between tunnel bore and atmosphere. Especially in the portal regions (shafts, slits, etc.)	Partial reflection of pressure waves amplitudes	Use of pressure relief shafts might lead to smaller cross-sectional tunnel areas - money saving measure. Shafts might be used as emergency exits.	Openings between bores might cause safety problems. Shafts might bring unpleasant effects in the surroundings (noise).
	Larger cross-sectional area	Lower blockage ratio leads to lower amplitudes.	Big cross-sectional areas reduce the traction power requirements. The operational costs might be reduced.	Higher construction costs.

2.4 Sonic Boom

2.4.1 Phenomena

Sonic boom causes an explosion-like "bang" at rail tunnel portals. The generation of a sonic boom effect is pointed out in figure 4. (1): A pressure wave is generated during train nose entrance. (2): The pressure wave travels through the tunnel and becomes steeper, but damped in amplitude. (3): The very steep pressure wave front hits the portal and leads to the irradiation of audible micro pressure waves: a Sonic Boom.

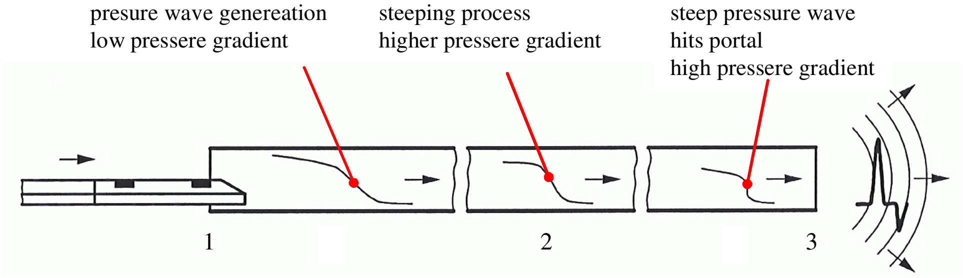

Figure 4: Sonic Boom as a result of a steepened pressure wave hitting a portal [3]

Sonic Boom normally occurs at the exit portal opposite to the pressure wave generation portal. To generate an audible boom the amplitude and steepness of the pressure wave have to be above a certain value. The height of the amplitude depends mainly on the train speed whereas the steeping process depends on tunnel roughness (e.g. ballast or slab track) and on the tunnel length. As shown in figure 5 the factor between the gradient of the wave at the entrance portal and the gradient at the exit portal strongly depends on the tunnel length (enough time for the steeping process). For tunnels with lengths of 7 km, an initial pressure wave gradient of about 13 kPa/s will be steepened by a factor of 10 while travelling through the tunnel.

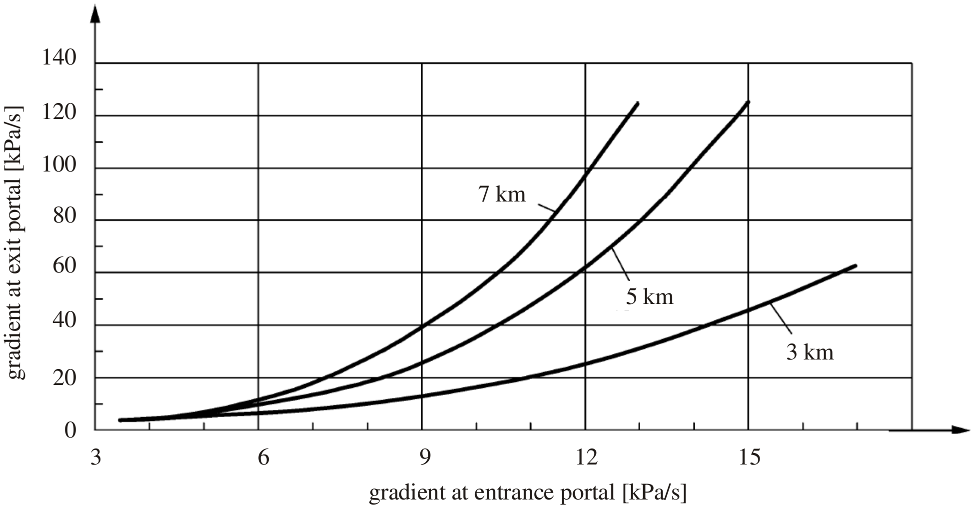

Figure 5: Pressure gradient steeping effect for different tunnel lengths (3, 5 and 7 km [3])

2.4.2 Assessment tools

The analysis required to determine if a Sonic Boom may occur is rather complicated, since several parameters have to be taken into account, e.g.: track design, tunnel length, train nose or tail design, trains speed, blockage ratio, etc. However simple algorithms may give a first rough estimation (e.g. [3]).

There is no analytical way of proving the efficiency of measures against sonic boom. Hence, numerical tools are needed for detailed planning. For normal cases it might be sufficient to work with 1d or 2d tools [10]. Complex situations and the complete simulation of the portal outside region may demand 3d numerical methods.

2.4.3 Measures to reduce unacceptable impact of sonic boom

Several solutions are used to avoid sonic boom on high-speed lines with tunnels. The most commonly employed measures are listed in table 6. All measures do have at least one major intrinsic drawback (costs, efficiency, lack of pressure comfort, etc.). Hence, it is of great importance to evaluate carefully the "best-project-sonic-boom-measure" individually for each tunnel (for possible advantages or drawbacks see also table 5 above).

Table 6: Measures to reduce sonic boom

Measure	**Description**	**Effect**
operative	Reduced train speed for entering or leaving a tunnel	Reduced pressure wave gradient and amplitude.
civil	Use of ballasted track instead of slab track	Strong damping of travelling pressure waves.
	Portal Design (e.g. trumpet shape)	Lower pressure wave gradient and amplitude.
	Openings between tunnel bores or between tunnel bore and atmosphere. Especially in the portal regions (shafts, slits, etc.)	Partial reflection of pressure waves (shafts, openings) or reduced pressure gradients and amplitudes due to partial pressure equalisation (slit) between tunnel and exterior.
	Larger cross-sectional surface	Lower blockage ratio leads to lower pressure wave gradient and amplitude.
	Installation of absorber materials on the tunnel surface.	Pressure waves will be strongly damped while passing the absorber material.
rolling stock	Train nose design / long shape	Long train noses will cause less steep pressure gradients while entering or leaving a tunnel.

3 Tunnel Safety and Tunnel Ventilation

3.1 Tunnel Safety

3.1.1 Basics

The main risks in railway tunnels are fire, collision and derailment. As a fire in passenger trains is a major and specific risk for tunnels with potentially catastrophic consequences, the paper focuses mainly on this type of incident.

According to the technical specification of interoperability relating to 'safety in railway tunnels' in the trans-European conventional and high-speed rail system (TSI SRT, [15]) the tunnel safety depends on a number of subsystems (cf. figure 6). All of them are equally important. The paper however concentrates mainly on the subsystem "infrastructure".

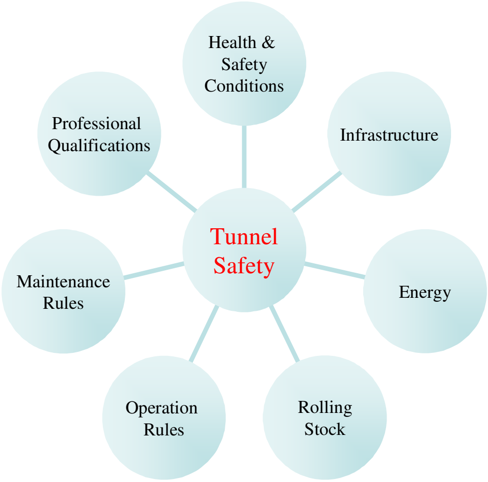

Figure 6: Subsystems relevant for railway tunnel safety according to [15]

In addition to the regulations specified in the TSI SRT the guidelines of the UIC Codex 779-9 [18] concerning tunnel safety have to be considered. TSI SRT defines only few mandatory measures whereas UIC gives a good overview over a more general set of possible safety measures and advice to the efficiency of these measures.

Along with the European guidelines there are a number of national guidelines as for example the German EBA guideline [1] or the Swiss guideline SIA 197 [11], [12]. In Austria the guideline of the national fire fighting association has to be respected [8]. These national guidelines occasionally lead to differing safety measures, as the following examples show:

- Water supply: In Germany dry water pipes in all tunnels longer than 500 m are mandatory whereas in Switzerland normally rescue trains (mobile water supply) are used and no fixed water pipes are foreseen in railway tunnels. In Austria permanently filled or dry pipes are demanded. However in very long tunnels as the 32.8 km long Koralmtunnel [7] a fixed water supply system is planned only in the underground emergency station. In the tunnel sections the water is brought into the tunnel by a rescue train.

- Ventilation: Another example is the ventilation of cross passages which connect two parallel tunnel tubes. According to the German EBA guideline airlocks without any mechanical installation to prevent a propagation of smoke to the parallel tunnel tube (safe area) are possible, whereas in Austria a mechanically generated overpressure corresponds to the generally accepted state of the art (see chapter 3.2.1).

In the absence of an agreed set of national guidelines it is therefore inevitable to develop specific railway tunnel safety concepts. According to [15] and [18] such safety concepts should be based on the following general principles:

- Prevention of incidents
- Mitigation of impact of accidents
- Facilitation of escape
- Facilitation of rescue

The order in which these are listed reflects their decreasing effectiveness in the case of a fire (see figure 7). It is important to note that measures preventing an incident in the tunnel (e.g. emergency brake neutralisation during a tunnel passage) are much more effective than measures which improve the self rescue of passengers or measures which support the rescue services.

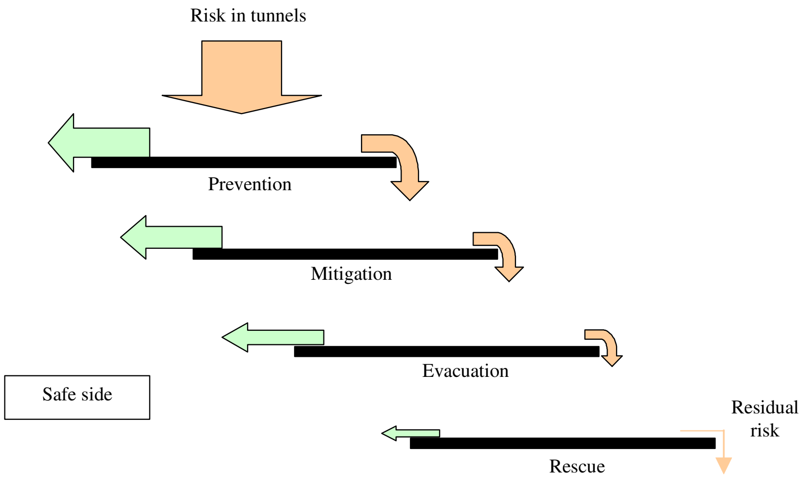

Figure 7: Hierarchy of safety measures

A safety concept generally consists of a combination of infrastructure, operations and rolling stock measures, which should be combined in a manner to achieve an optimised concept. It is important to note that the definition of specific safety measures in a project should be based on an assessment of the risk (risk based safety concept).

3.1.2 Infrastructure safety measures

In the planning of a new railway tunnel some of safety measures greatly influence the tunnel design. These have therefore to be taken into consideration at a very early phase of a project, and a number of fundamental decisions have to be taken. As these decisions influence not only the safety but have also wide impacts on the overall construction and operation costs of a tunnel system a closer examination is necessary.

The most important decisions, which have a direct impact on the tunnel design, are:

- Tunnel system: The decision if a single bore double track or double bore single track tunnel should be built has not only a major impact on the safety level but also on the costs of a tunnel project.
- Rescue concept: If tunnel access with road vehicles is foreseen a track fit for road vehicles must be built and direct access to the portal must be ensured. These measures can be, at least partly, omitted if a special rescue train is used. In this case however appropriate trains as well as tracks where the rescue train can be stored have to be provided.

Other infrastructure measures which have a major influence on the tunnel project are:

- Escape distance: The maximum distance of cross passages (in double bore tunnels or in tunnels with a parallel service and safety tunnel) or distance of emergency exits in single bore tunnels is stipulated in the TSI SRT (maximum 500 m for tunnels with a parallel tube or maximum 1000 m for a double track tunnel). However, some of the very long double bore tunnels planned or built in the last years have considerably lower distances (see table 7).
- Rescue areas at tunnel entrance or exits: The TSI SRT defines a minimal area of 500 m^2. National regulation however demand often distinctively higher areas (e.g. 1500 m^2 [1], [8]).
- Tunnel ventilation: If a tunnel ventilation system is needed (see chapter 3.2) these may also have a major impact on the tunnel design (location of exhaust shafts and required space for ventilation plants).

Additionally the following infrastructure safety measures have to be provided:

- Escape walkways: Lateral walkways inside the tunnel with a minimal width of 0.7 m must be provided. Optimally the width of walkways should be 1.2 m.
- Arrangement of switches: The location of switches or other track discontinuities help to prevent incidents and it is therefore recommended to optimise their arrangement. In tunnels and at the approach to tunnel entrances, the installation of switches should be avoided.
- Fire protection for structures: Especially for under water tunnels or tunnels in urban areas with infrastructure as roads or buildings over the tunnel special consideration has to be taken to the fire protection requirements for structures. Normally a standard temperature curve can be used if no higher risks are expected.

3.2 Tunnel Ventilation

3.3 State of the art

Whereas road tunnels longer than 1000 m are generally equipped with a mechanical ventilation system, railway tunnels normally do not have any mechanical ventilation. Only in very long tunnels or in tunnels with special features ventilation systems are installed. Table 7 gives an overview over the few tunnels with a mechanical ventilation system which are already in operation and the special features which justify mechanical ventilation systems for these tunnels.

For the ventilation of railway tunnels no specific guidelines exist up to now. This is due to the lower risk compared to a road tunnel where national guidelines are generally available. The necessity of a mechanical ventilation system in a railway tunnel must therefore be proven for each single tunnel.

Table 7: Railway tunnels with mechanical ventilation systems

Tunnel	**Length**	**Cross passages**	**Special features**
Channel Tunnel	50.5 km	375 m	lorry transport
Lötschberg Base Tunnel	34.6 km	333 m	underground emergency station
Tunel de Guardarrama	28.4 km	250 m	
Great Belt Tunnel	8.0 km	250 m	underwater tunnel

There is however an increasing number of tunnel projects where a mechanical ventilation system is planned. As an example, table 8 lists the actual tunnel projects in Austria with a ventilation system.

Table 8: Austrian railway tunnel projects with mechanical ventilation

Tunnel	**Length**	**Ventilation System**	**Special features**
Wienerwald Tunnel	13.4 km	overpressure in cross passages, fans situated in each cross passage	connected to Tunnel Lainz (double track single bore)
Koralm Tunnel	32.8 km	overpressure in the parallel tube, fans in two eccentric shafts	underground emergency station
Semmering Base Tunnel	28.4 km	negative pressure and smoke exhaust from incident tunnel, fans situated in a central shaft	underground emergency station
Granitztal Tunnels	6.0 km	negative pressure smoke exhaust from incident tube, fans situated in a central shaft	2 tunnels connected by a cut and cover section
Brenner Base Tunnel	55.0 km	overpressure to incident tube, smoke exhaust from emergency station	underground emergency station, underground connection to existing tunnel (Innsbruck bypass)

It has to be pointed out, that these ventilation systems guarantee only smoke free areas creating a pressure difference to the incident tube but they do normally not influence the smoke movement in the incident tunnel itself. Smoke exhaust systems are generally only foreseen for emergency stations.

In addition there is a big number of shorter tunnels with lateral or vertical exits equipped with a ventilation system to guarantee an overpressure inside the escape exit to the tunnel and thus keeping the escape route free of smoke.

3.3.1 Objectives / protection goals

Due to the lack of guidelines for railway tunnel ventilation projects specific safety objectives and protection goals have to be defined. Typically the following topics should be covered:

- Normal operation: The climate inside the tunnel must be maintained within a certain range. This aspect is especially important in very long tunnels with high overburden where high temperatures can result due to the thermal flow from the surrounding rocks and the waste heat from the trains.
- Maintenance: During periods of maintenance work a sufficient dilution of exhaust gases from diesel trains and other machinery in operation for maintenance must be guaranteed to comply with occupational health and safety requirements.
- Tunnel fire: In the case of a tunnel fire a safe area has to be guaranteed, in which the passengers can escape. This may be a parallel tunnel tube or in very long tunnels a special emergency station (see chapter 3.3.1). In these safe areas survivable conditions have to be maintained over an extended time period. A method to prevent smoke penetrating in the safe area is to provide an airflow of typically 2 m/s from the safe area towards the incident tube (see figure 8).

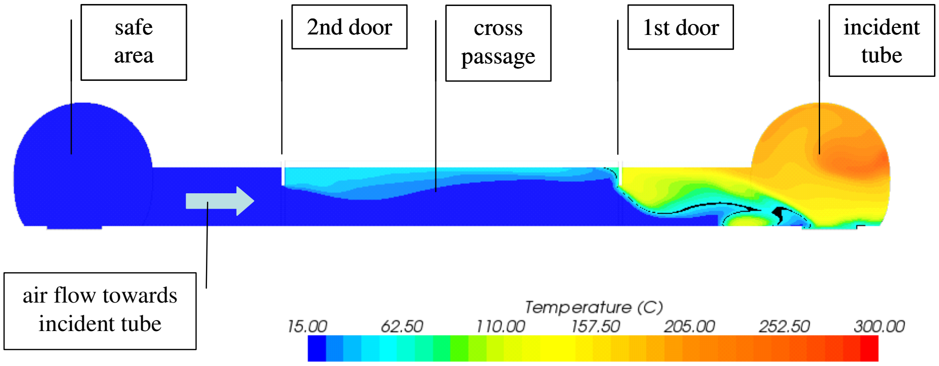

Figure 8: CFD Simulation of the smoke propagation into an open cross passage under the action of a airflow through the cross passage from the safe area (left side) to the incident tube (right side).

3.4 Very long tunnels

3.4.1 Emergency stations

According to TSI SRT [15] "appropriate provisions must be laid down to take account of the particular safety conditions in very long tunnels".

The probability that a burning train can't reach the portal (safe area) increases with increasing tunnel length. According to TSI RST a passenger train should maintain its movement capability for 15 minutes, so that in the case of a train fire inside a tunnel, the train is expected to reach the tunnel portal. Assuming a train speed of 80 km/h only tunnels which are significantly longer than 20 km are therefore normally equipped with a emergency stations. Table 9 gives an overview of railway tunnels with such underground emergency stations.

Table 9: Railway tunnels and tunnel projects with underground emergency stations

Tunnel	length	Number of emergency stations
Lötschberg Base Tunnel	34.6 km	1
Gotthard Base Tunnel	57.0 km	2
Brenner Base Tunnel	55.0 km	3
Koralmtunnel	32.8 km	1 (no direct connection to surface)
Semmering Base Tunnel	28.4 km	1
Lyon Turin Base Tunnel	53.1 km	1 + 3 interventions sites[1]

These emergency stations are used to allow a burning train to stop and are designed in a way that a safe and fast evacuation of a train is possible. The passengers then wait in a safe area nearby until they can be transported outside by a train entering the second tube.

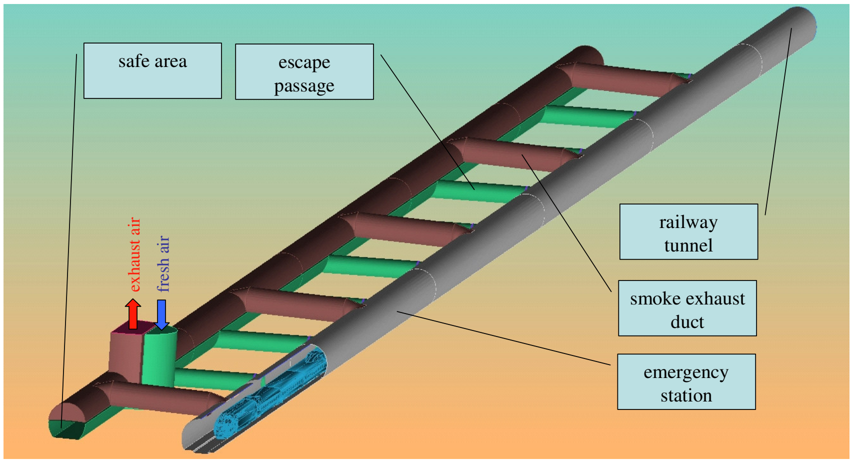

Figure 9: Possible layout of an underground emergency station

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[1] for freight trains only

3.4.2 Train operation in the case of a tunnel fire

Another aspect which has to be considered in long tunnels is the fact that several trains may be in the tunnel system simultaneously. This has multiple consequences for the operation in an emergency situation:

- Following trains: A fire may endanger trains following the incident train which is trapped behind the burning train. Emergency procedures must therefore be put in place to stop following trains as quickly as possible.
- Influence on airflows/ventilation: The movement of rescue or fire fighting trains does have a direct influence on the airflows in the tunnel (piston effect) and may compromise the functioning of the ventilation or smoke exhaust system. The maximum speed of these trains must therefore be limited to guarantee that the ventilation and the smoke exhaust system perform properly.

Additional information to these important aspects can be found in [7].

4 Conclusions

Tunnel design processes for modern railway tunnels have to take different interdependent domains into account. Some of most significant aspects are shown in figure 10. For practical reasons and in order to provide efficient and cost-effectiveness civil planning, it is of highest importance to evaluate the impact of tunnel aerodynamics and tunnel safety in the initial planning phase as these aspects play a crucial role in the planning process.

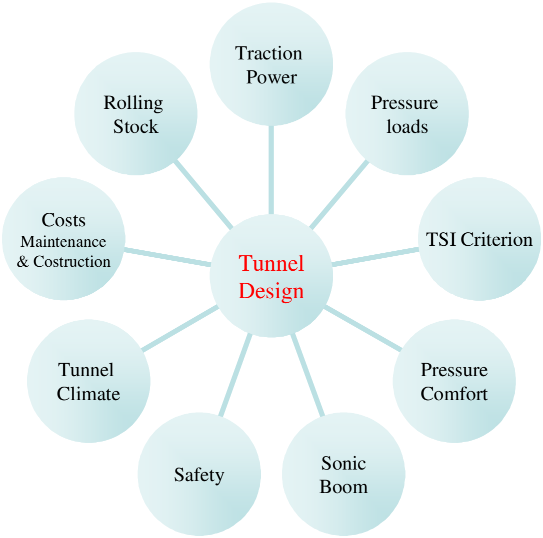

Figure 10: Interdependency of civil engineering work and adjacent domains

5 Acknowledgements

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