TWIN-TUBE, SINGLE-TRACK HIGH-SPEED RAIL TUNNELS AND CONSEQUENCES FOR AERODYNAMICS, CLIMATE, EQUIPMENT AND VENTILATION

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SYNOPSIS
High-speed rail tunnels are designed increasingly as twin-tube, single-track systems. In general, these tunnels are considered to be safer, particularly due to the reduced probability of collision of trains and due to the better escape and rescue conditions. Additionally, twin-tube systems allow safer maintenance operation because one of the two tubes can be shut down completely during this mode of operation, while the parallel tube remains in operation. The disadvantages of twin-tube rail tunnels are, in general, higher construction and operation costs.

In comparison with single-tube systems, particular differences in the field of aerodynamics, climate, equipment and tunnel ventilation in double-track systems, especially in high-speed rail tunnels, have to be considered. The particular aspects of this paper are:

- comparison of the aerodynamic conditions (pressure fluctuations, air velocity, traction power requirements, probability of micro-pressure waves)
- characterization of the climatic conditions (temperature and humidity, etc.)
- highlighting the differences of the ventilation modes
- presentation of some specifications for the tunnel equipment (closure and air conditioning of cross-passages, design of cabinets)

The aim of the paper is to create a better understanding of the above aspects for the design of future rail tunnels.

1 INTRODUCTION

In Asia and Europe, the network of high-speed tunnels with velocities of over 250 km/h has significantly been increased in the previous decades. Parts of these rail links are placed in tunnels, which are mostly designed as single-tube, double-track systems. Tunnel systems using double-tube, single-track rail tunnels have been built and operated since the early days of rail tunnels. For geological, functional or other reasons, this design seemed to make more sense under the specific boundary conditions of their location.

So far, the combination of both, high-speed tunnels with velocities of over 250 km/h and twin-tube single-track tunnels is quite rare. However, various high-speed tunnels being in the planning stage or under construction now are foreseen to be built as of this type. The conceptual change from double-track to single-track tunnels affects the aerodynamics, the climate, the ventilation and other equipment or civil design of which the designer needs to be aware.

2 PURPOSE AND FOCUS OF THIS PAPER

The aim of this paper is to provide a better understanding of an integral design of future rail tunnels as well as to suggest improvements considering the following aspects:

- aerodynamics (pressure comfort, traction power, micro-pressure waves)
- climate (temperature, humidity, dust, pollutants, natural gas)
- ventilation (normal, maintenance, disturbed and emergency mode of operation) and fire safety
- civil design and equipment; cross-passage design

The above aspects are closely related to tunnel ventilation. Generally speaking, tunnel ventilation in a narrow sense is associated with fans, dampers and their control systems. Tunnel ventilation in a broader sense includes aspects like:

- ventilation during normal operation, congested traffic operation, maintenance operation to maintain adequate climatic conditions
- emergency operation, general safety concept and integration of ventilation measures (rescue and intervention concept)
- tunnel aerodynamics (pressure waves, pressure comfort, traction power, drainage system) and climate
- equipment directly related to ventilation (fans, dampers, ducts, control and detection systems, power supply)
- further mechanical equipment (cabinets, doors, handrails, signalling, air-conditioning of technical rooms, etc.)

These issues are closely linked together. For example, the mechanical equipment in a tunnel often serves to support ventilation objectives or it has to fulfil specifications mainly concerning ventilation or aerodynamic issues.

3 VARIANTS, FEATURES AND LEGISLATION OF TWIN AND DOUBLE-TUBE RAIL TUNNELS

3.1 Tunnel systems

Twin and single-tube tunnel systems can be designed in different ways. Figure 1 shows some examples of various possible combinations and arrangements of rail tunnel systems. Certain systems are considered as single-tube systems from a civil engineering point of view but as twin-tube system from aerodynamic, ventilation or safety point of view (see Figure 1; Var. 4 or 6).

Similar to the civil design, the requirements from a ventilation point of view may differ significantly, depending on location, rock or water overburden, train types, operation, etc. In the following, only the typical twin-tube single-track system (see Figure 1; Var. 1) and the single-tube double-track system (see Figure 1; Var. 8) are considered.

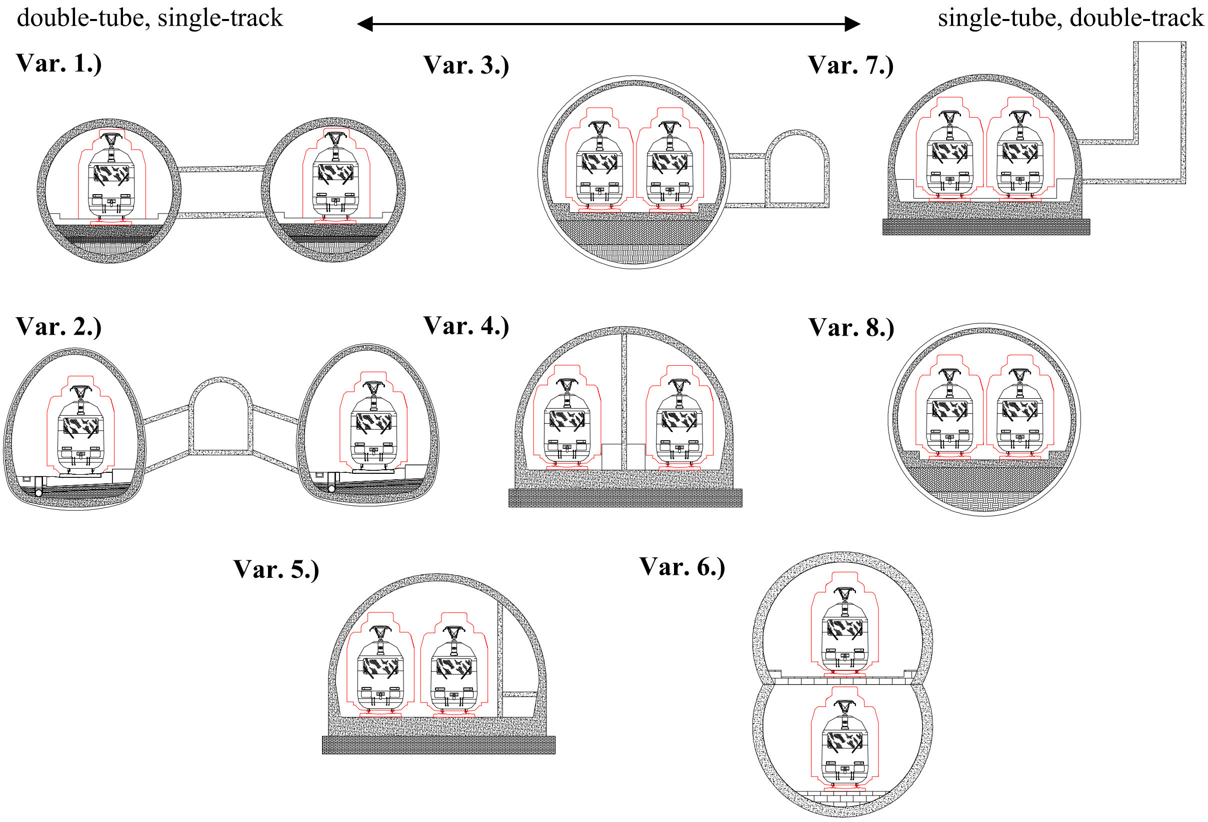


Figure 1: Variants of double- and single-tube rail tunnel systems

3.2 Characteristic consequences of changing from double to single track

As an introduction, Table 1 lists some qualitative effects of changing the tunnel system from a single-tube, double-track to a double-tube, single-track tunnel. Table 1 focuses on issues related to aerodynamics, climate, ventilation, safety and equipment, ignoring further civil or operational differences.

	Aspect	**positive: +; negative: -**	**Remarks concerning various aspects, when changing tunnel design from single to twin-tube**
1.	pressure forces on trains, tunnel walls and equipment	-	more extreme pressure deviations from normal pressure; across cross-passages pressure variations of single tube must be added up (walls, doors); more mechanical resistance or air-tightness necessary for equipment
2.	pressure comfort	-/+	due to smaller cross-section more extreme pressure fluctuations; better pressure comfort due to no mutual interference with upcoming trains
3.	wind loads	-	more extreme winds in tunnel and more mechanical resistance necessary for equipment
4.	micro-pressure waves	-	increased probability of micro-pressure waves (sonic boom) at least with slab track
5.	traction power requirements	-	higher power demand due to increased friction in smaller cross-section; alleviation possible by open cross-passages during normal operation
6.	climate	+/(-)	enhanced air exchange due to predefined, regular longitudinal air flow in the tunnel due to the unidirectional traffic; slightly increased traction power consumption and increased heat release
7.	safety during normal operation	+	reduced probability of collisions and consequences of derailment
8.	safety during maintenance	+	better working conditions and safety since no regular trains in maintenance tube; traffic only in non-maintenance tube
9.	safety tunnel ventilation	+	enhanced longitudinal ventilation in the first seconds of a train fire; predefined air flow in the tunnel due to the unidirectional travel; better pre-defined conditions and flow directions
10.	safety during emergency	+/-	significantly shortened escape and rescue distance to non-affected, protected region, i.e. parallel tube protected against fire and release of hazardous gases; shorter evacuation time available in the first important seconds of a train fire due to smaller cross section; less space for rescue operation
11.	ventilation during construction	+	particularly for long tunnels less ventilation power and equipment necessary; tubes used as loop for supply and removal of air
12.	investment costs	-	in general higher depending mostly on geology

Table 1: Selected consequences of changing from a single-tube, double-track to a twin-tube, single-track tunnel; focus on aerodynamics, climate, ventilation, safety and equipment

Both, single-tube, double-track and double-tube, single-track tunnels have their advantages and disadvantages concerning safety. Double-tube, single-track tunnels might be safer as there are no accidents caused by derailments obstructing the adjacent track. Additionally, they provide the second tube as a possible safe haven. On the other hand, double-track tunnels have more space for possibly necessary rescue operations, but they also have more space for smoke and fire to spread (see Figure 10). For high-speed trains, single-tube, double-track tunnels might be preferable and for mixed traffic, a single-tube single-track might be more appropriate. The choice should be the result of a thorough evaluation of all parameters (such as length of the tunnel, type of traffic, possibility for adits or galleries, etc.) related to safety as well as cost considerations. As shown in Table 1, it is mainly the safety aspect and partly an improved tunnel climate, which lead to the current preference of twin-tube, single-track tunnels for high-speed rail lines. Apart from cost and possible other civil construction disadvantages, the negative consequences affect mainly the tunnel aerodynamics and the more stringent requirements for tunnel equipment.

3.3 Current recommendations in Europe

Traditionally decisions about tunnel systems are based on geology, location, function and cost. Decisions on tunnel safety are influenced by aspects such as the possibility of self rescue on escape routes, cross-passages or emergency exits, availability of emergency services, ventilation, drainage system and prevention of explosion and the operation concept (passenger trains, mixed traffic, shuttle trains). Therefore, the decision spectrum is quite heterogeneous and often based on an evaluation of each single project. Table 2 shows examples of the current recommendations for high-speed rail tunnels in some European countries. The guidelines might include a temporal, local or scheduled separation of freight and passenger traffic.

	Country	Guidelines or practice for high-speed tunnels being at the conceptual or planning stage
1.	France	- existing high-speed rail lines with only a few tunnels - mostly double-track - new tunnels with mixed traffic and a length of more than 5 km are built as twin-tube systems
2.	Germany	- distinction between short tunnels (500 – 1‘000 m); long tunnels (1‘000 – 15‘000 m) and very long tunnels (> 15‘000 m) - single-tube, double-track tunnels used for passenger trains only - passenger and freight trains: for distances over 1‘000 m only single-tube, double-track tunnels - passenger and freight trains: from 500 m to 1‘000 m, scheduled trains should not meet in tunnel
3.	Italy	- mainly single-tube, double-track tunnels on new high-speed lines
4.	Netherlands	- double-tube, single-track for new high-speed lines (e.g. Groenehart)
5.	Switzerland	- project dependent - tunnel purely for passenger trains (e.g. 5 km): single-tube, double-track - tunnel for mixed traffic (e.g. 15 km): double-tube, single-track
6.	UIC	- project dependent - twin-tube tunnels recognised as a high risk mitigation for long tunnels

Table 2: Guidelines and examples concerning choice between single and twin tubes tunnels in Europe

4 CONSEQUENCES OF CHANGING FROM SINGLE- TO TWIN-TUBE SYSTEMS

One-dimensional simulations based on boundary conditions as described in Appendix A have been performed. The simulations concerning the aero- and thermodynamics in twin- and single-tube tunnels illustrate the impact of the design.

4.1 Tunnel aerodynamics

The aerodynamics includes various aspects such as:

- pressure forces acting on trains, tunnel wall and doors, cabinets and air ducts and fans
- medical pressure limits and pressure comfort in the trains and in the tunnels during normal and maintenance operation
- air velocity, i.e. safety and comfort of maintenance personal and wind loads on equipment in tunnel and on rolling stock (e.g. freight on trains)
- exchange rate of air, i.e. consequences of heat removal, humidity, pollutants, dust, natural gas, etc.
- traction power requirements of trains
- occurrence of micro-pressure waves at exit portal (sonic boom)

4.1.1 Pressure waves

When a train enters the tunnel, a pressure wave is generated, which propagates with the speed of sound as a compression wave along the tunnel to the exit portal. At the exit portal, it is reflected and travels back as an expansion wave. These pressure waves together with the pressure differences along the moving train act on the train structure, the tunnel wall, the installed equipment and the people travelling on the train.

The magnitude of the pressure fluctuations is a result of the speed, the cross section, the shape and the roughness of the train and the length, roughness and the civil construction of the tunnel and portals. In general, a smaller cross section, i.e. an increased blockage ratio, creates more extreme pressure fluctuations.

Figure 2 shows the magnitude of the pressure deviations from normal pressure in a twin-tube and a single-tube tunnel (see Appendix A for input of calculations). It is evident that due to the smaller cross section of the twin-tube tunnel more extreme pressure deviations from normal pressure occur. However, in a single-tube double-track tunnel two trains can pass each other. In that case, pressure extremes might be as high as in the twin-tube tunnel.

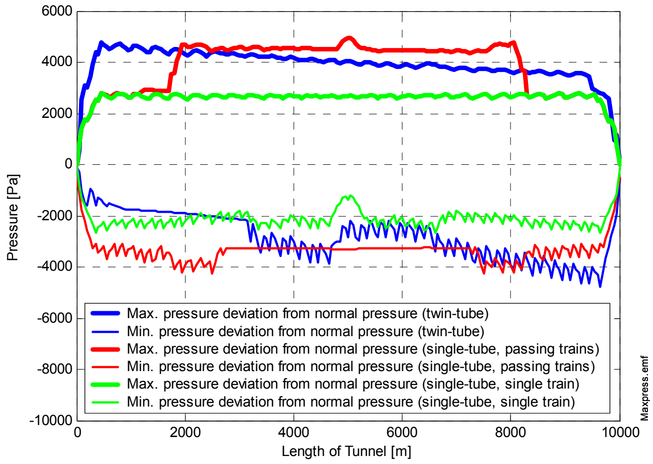


Figure 2: Range of pressure deviation from normal pressure along a tunnel after several train passages through tunnel (see Appendix A); more extreme deviations possible due to changes of the schedule

In the example of Figure 2 the pressure deviates from the normal pressure in the range of approximately +/- 5 kPa. Figure 3 illustrates the resulting pressure loads on walls of cross-passages of a twin-tube system. If the pressure generated by trains in one tube is +/- 10 kPa, the pressure difference acting across the cross passages (and hence the doors) might reach 20 kPa.

Additionally, Figure 3 shows the difference of static and dynamic pressures. Differences of the static pressures lead to forces on walls, doors, cabinets, covers of shafts, etc. Wind induced dynamic pressures act on signs and other objects in the rail tunnel (see section 4.1.3).

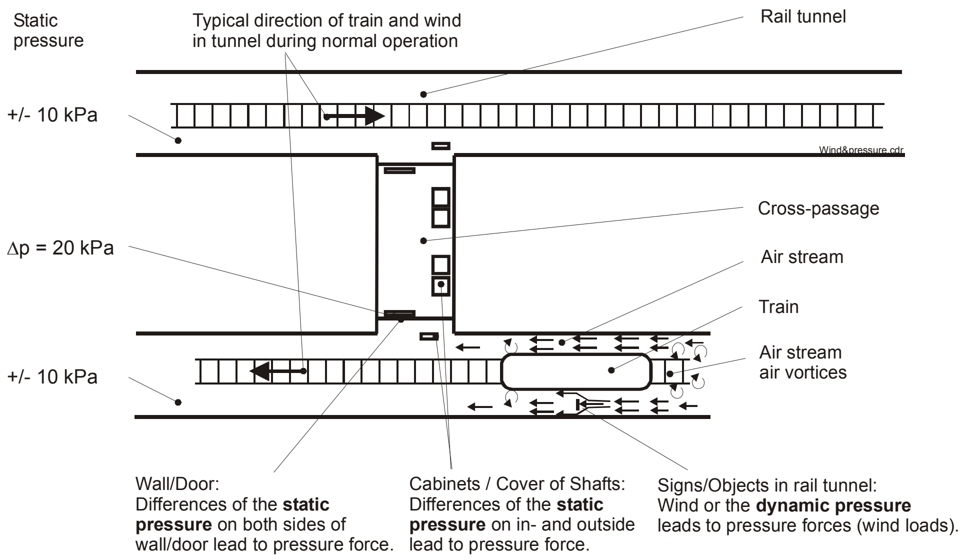


Figure 3: Possible pressure deviation from normal pressure in one tube (+/- 10 kPa) and pressure differences on cross-passage walls/doors (20 kPa) in a high-speed twin-tube tunnel and wind loads

4.1.2 Pressure comfort

The human organs of hearing react quite sensible on pressure fluctuations in short time intervals. Pressure fluctuations in tunnels are usually not harmful and the magnitude of pressure fluctuations is smaller than during the flight in a plane. However, they might cause significant discomfort for passengers in trains because the pressure fluctuations appear in rather short time. Both, international (UIC) and numerous national norms give limits for the acceptable pressure changes in time. As an example, Figure 4 shows the pressure change within a time interval of 3 s. The relevant UIC recommendation limits this pressure change in a time interval of 3 s to 800 Pa [1].

Figure 4 illustrates that single-tube tunnels with larger cross-section easier maintain pressure comfort limits than adequate twin-tube tunnels with smaller cross-section. Frequent passages of trains in a single-tube, double-track system might lead to pressure discomfort. Measures to alleviate the pressure comfort can focus on:

- rolling stock (pressure-tight trains, better streamlined trains, lower velocity)
- tunnels (shafts near portal, perforated walls, trumped-shaped portals)

4.1.3 Wind loads

The wind loads acting on trains, equipment or maintenance personal are linked to the pressure waves, i.e. pressure fluctuations lead to high wind velocities.

The effect of reducing the cross section on the maximum design velocity of air in the tunnel shows in Figure 5. Figure 5 results from measurements and is used as a design recommendation for tunnel equipment. As illustrated, changing from a single- to a twin-tube system, which might correspond to a reduction of the cross-sectional area from 70 m^2 to 45 m^2, leads to increased wind loads in the tunnel during the immediate passage of trains by 50 %.

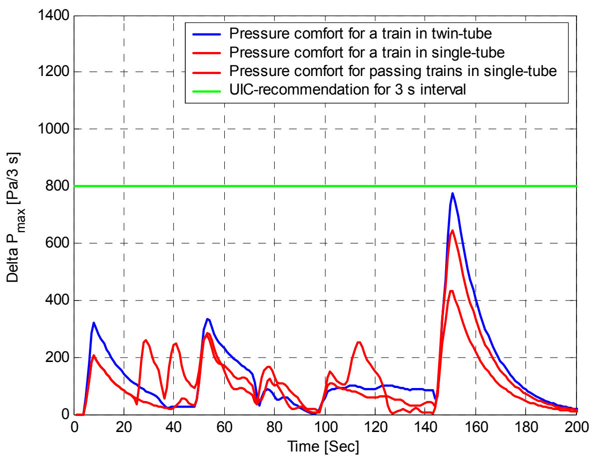


Figure 4: Max. pressure fluctuation within a 3 s interval (see Appendix A for description)

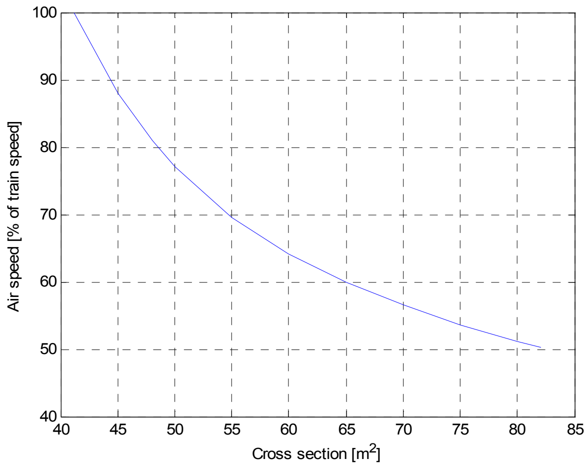


Figure 5: Maximum design air velocity in tunnel [2]

4.1.4 Traction power requirements of trains in tunnels

Due to higher friction and pressure losses, the power demand for a single train travelling in a single-tube, double-track tunnel with larger cross-section is lower than in a twin-tube, single-track tunnel (see Figure 6). This effect is slightly compensated by the prevailing unidirectional flow of air in the twin-tube, single-track system, particularly, with a high frequency of trains.

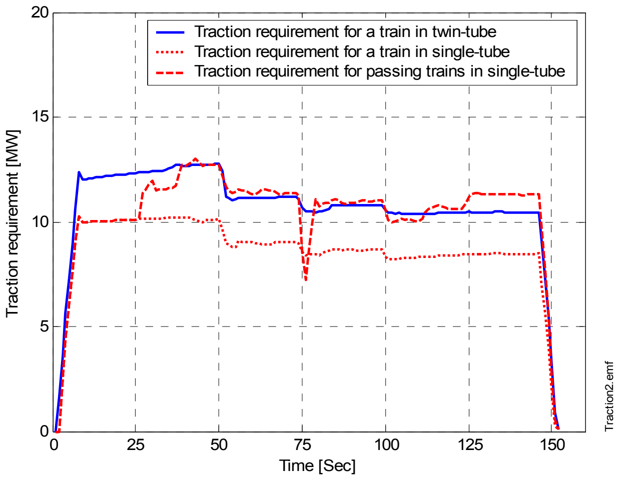


Figure 6: Traction power requirements in tunnel (see Appendix A for description)

4.1.5 Micro-pressure waves

At high train speeds and an unfavourable tunnel and train design, the pressure wave generated at the entrance portal becomes steeper during propagation through the tunnel. The pressure wave, propagating at the speed of sound, might create a detonation like sound when reaching the exit portal (sonic boom; see Figure 7).

In general, the probability of creating non-acceptable pressure fluctuations at the exit portal increases with smaller cross-sections at the entrance portal and with change from ballast to slab track. As the velocity of the train increases linearly at the portal entry, the amplitude of the pressure wave augments in a quadratic and the gradient of the pressure wave in a cubic manner.

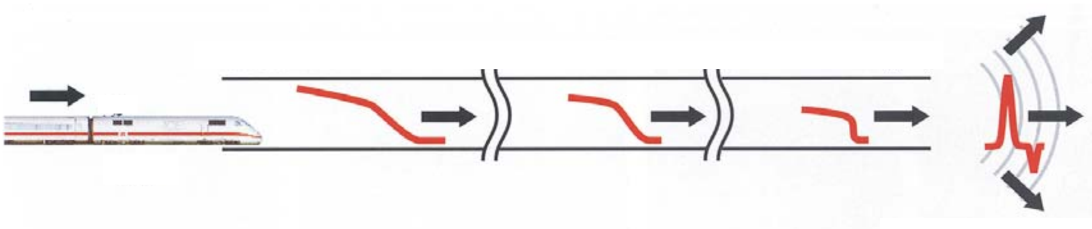


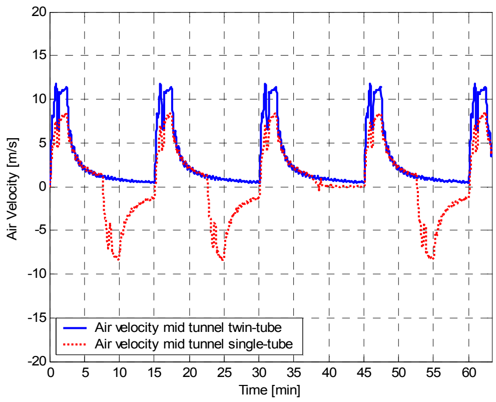
Figure 7: Development of micro-pressure waves (Sonic boom phenomena; illustration of German Rail)

4.2 Tunnel climate

The climate of a tunnel is described by the temperature, the humidity, the velocity of air and the concentration of dust, pollutants or natural gas. Heat from the ground, the technical installations and trains (traction power, air conditioning) influence the climate. Additionally, the rate of air-exchange with the ambient via portals and shafts and the weather conditions determine the climatic conditions in the tunnel.

In general, the train induced air exchange is sufficient to provide acceptable conditions during normal operation. Unidirectional traffic as in a double-tube, single-track system promotes an efficient exchange of air. On the contrary, in a single-tube tunnel, the air tends to oscillate depending on the natural and train induced ventilation. Under certain but rare circumstances, the core of the air the tunnel remains in the tunnel during several days.

The piston effect of the running trains is mostly sufficient for the ventilation of a tunnel. Figure 8 shows the air velocity in the mid tunnel of a twin-tube and a single-tube tunnel. It is evident that due to the unidirectional traffic a continuous longitudinal air velocity prevails in the twin-tube tunnel.



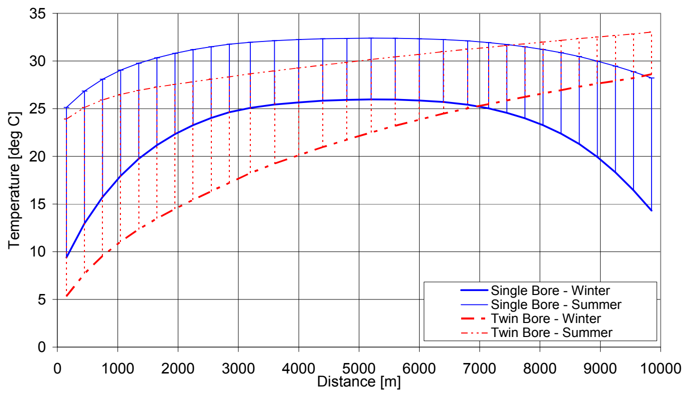


Figure 8: Air velocity in the mid tunnel (1-dim. calculation; see App. A)

Figure 9: Temperature distribution in the tunnel (see Appendix A for the underlying specific boundary conditions)

The influence and direction of the longitudinal flow affects the climate in the tunnel (see Figure 9). While in a single-tube tunnel the temperature reaches a maximum in the middle of the tunnel, in a twin-tube tunnel the temperature increases continuously in the direction of the trains.

In certain tunnel systems, climatic conditions are crucial and a double-tube system is better to enhance the air exchange (e.g. long Alpine tunnels). In this case, measures to prevent air from re-entering the tunnel might become necessary. Else, exhaust air might re-enter in the system by the parallel tube. Measures for double-tube systems might include arranging the two portals in a staggered manner or installing shafts. Additionally, cross-passages or crossovers should remain closed in order not to deteriorate the positive effect of a double-tube system on tunnel climate.

4.3 Tunnel ventilation

The following sections address the specific requirements for ventilation during normal, maintenance, disturbed and emergency mode of operation.

4.3.1 Normal operation

The vast majority of high-speed rolling stock is purely electrically propelled, which makes consideration of pollutants due to diesel-propelled emissions unnecessary. Critical tunnel systems might be:

- heavily frequented subway systems
- very long tunnels
- tunnels in tropical and subtropical regions
- high rock temperatures
- diesel propelled trains

Under such critical boundary conditions, twin-tube tunnels have better performance because of the unidirectional, continuous airflow, which leads to a more efficient air exchange.

4.3.2 Congested or disturbed operation

The tunnel climate should still be within accepted limits even at times of abnormal traffic. Occasionally trains need to stop due to track blockage, power cut off or other reasons. Staying stationary for several minutes or even hours might lead to an unacceptable temperature rise because of release of waste heat (air-conditioning, cooling facilities, etc.). Both, single- and twin-tube tunnels have their advantages concerning the congested or disturbed mode of operation. A single tube, double-track tunnel allows taking in more heat due to its larger volume (see Figure 10). Additionally, if trains can still run on the parallel track, these provide a minimum air exchange. On the other hand, double-tube systems allow for ventilation that is more efficient.

4.3.3 Maintenance operations

During maintenance work, it is often required to restrict the train traffic or in the worst case stop all train movement. This can affect a single bore tunnel more than a twin-bore, as no alternative route is possible when people are working in the tube. Twin-tube systems allow in principle to shut down one tube and operate the other in bi-directional manner. This allows maintenance without train operation in the same tube resulting in significantly improved safety for the workers. The use of diesel propelled locomotives during maintenance or when dust is generated, might increase the need for ventilation. In this respect, double- tube, single-track systems are more favourable, because they allow a more efficient ventilation.

4.3.4 Emergency operation

Even though fires in rail tunnels are very rare, their consequences can be catastrophically, due to the high density of people and generally less efficient escape and rescue conditions compared with road tunnels. In an emergency, it is most important to control the dispersion of smoke. While natural ventilation allows the removal of smoke only under certain boundary conditions, mechanical ventilation allows full control of the smoke dispersion. Due to their smaller cross-section, a twin-tube, single-track system fills quicker with smoke than a single-tube tunnel (see Figure 10). Additionally, the limited size of the tunnel tube is a potential bottleneck for people escaping from the train and less space is available for rescue services in twin-tube tunnels. On the other, a twin-tube, single-track system, equipped with cross-passages and a ventilation system, provides significantly shortened escape and rescue ways to smoke-protected regions in the tunnel.

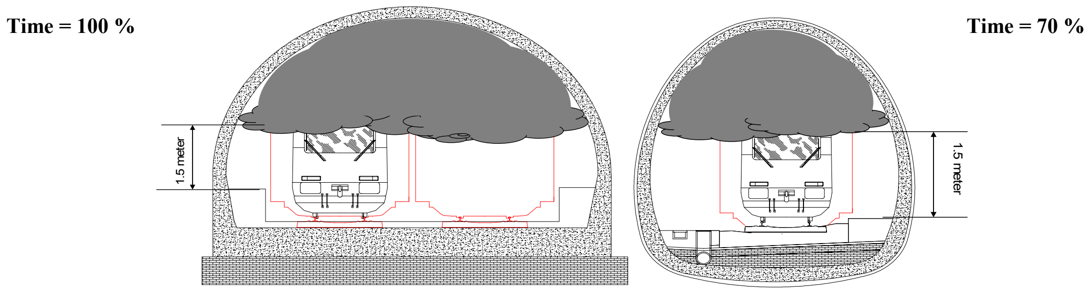


Figure 10: Stratification of smoke in a single-tube and twin-tube tunnel and different times for filling of the cross-section with smoke

In difference to road tunnels, in rail tunnels local smoke extraction is not applied. Exceptions are underground stations. Major principles of ventilation in a rail tunnel are:

- *Longitudinal flow of air/smoke in incident tunnel:* The objective is to achieve the critical velocity, i.e. no backlayering of smoke, which will protect fleeing passengers upstream of the fire from the effects of the smoke (see Figure 11) and which provides a defined access for rescue and fire fighting services.
- *Pressurisation of the escape routes:* The objective is to provide a flow of air towards the incident tube when cross-passages are open.

Longitudinal ventilation inherently implies the risk of moving smoke in the direction of escaping passengers and rescue services. Even if the position of a fire is known exactly, e.g. in the middle of a train, this dilemma cannot be eliminated unless local smoke extraction is applied. However, operating the ventilation system in a proper manner can moderate the harmful effects of this ventilation principle. For example, a moderate air velocity at the beginning of an incident will support the smoke stratification. The advantage of providing defined conditions outweighs by far the disadvantages of the longitudinal ventilation.

The main difference between single- and double-tube systems is the shorter average distances from an incident to a smoke free environment (at least for Var. 1 and Var. 8 of Figure 1). Ventilation allows pressurizing the non-incident tube, thus, preventing smoke from entering the cross-passages and the non-incident tube.

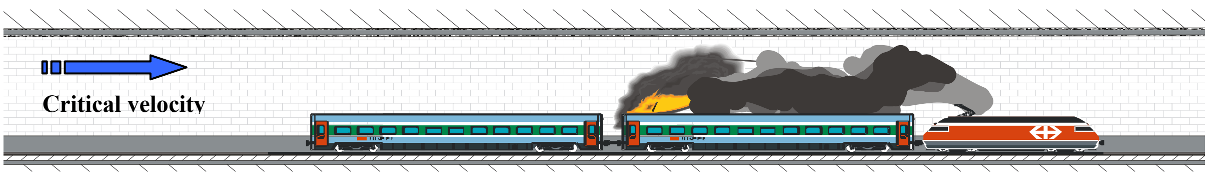


Figure 11: Critical velocity applied in a tunnel section to prevent backlayering of smoke

Different ventilation principles are shown for single- and for twin-tube tunnels.

- Ventilation in single-tube tunnel with ventilation station (see Figure 12)
- Ventilation in single-tube tunnel with jet fans (see Figure 13)
- Ventilation in twin-tube tunnel with ventilation station (see Figure 14)
- Ventilation in twin-tube tunnel with jet fans (see Figure 15)

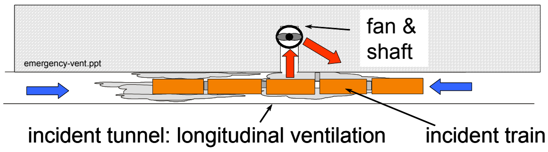


Figure 12: Ventilation in single-tube tunnel with ventilation station

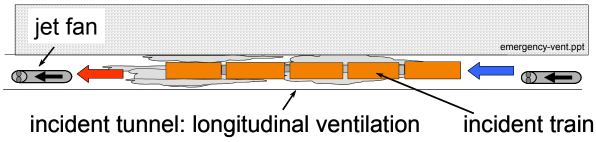


Figure 13: Ventilation in single-tube tunnel with jet fans

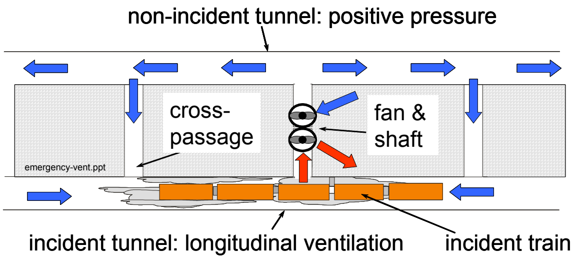


Figure 14: Ventilation in twin-tube tunnel with ventilation station

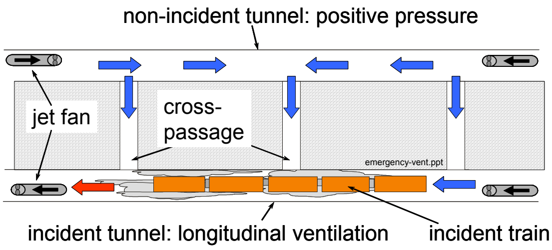


Figure 15: Ventilation in twin-tube tunnel with jet fans

4.3.5 Ventilation measures of current projects

Various rail tunnel projects in Europe are at the design stage or under construction at the moment. All of the examples shown in Table 1 of Appendix B with examples of more than 6 km in length are designed as twin-tube systems. Due to safety considerations twin-tube are preferred for increasingly shorter tunnels. The tunnels are mostly equipped with a mechanical ventilation system.

4.4 Design of cross-passage

In a double-tube system, the cross-passages design has to fulfil various requirements. Questions to be answered are listed in Table 3. Additionally, Table 3 summarises the operation modes for which these are relevant and the origin of the issue (aerodynamics, climate, etc).

	Design issue concerning cross-passages and others	**Operation Mode**				**Specification Origin**			
		Normal	**Maintenance**	**Disturbed**	**Emergency**	**Aerodynamics**	**Climate**	**Fire safety**	**Ventilation**
1.	What are reasonable design loads / strength for walls and doors?	x				x			
2.	What are reasonable doors for cross-passages?	x	x	x	x	x	x	x	x
3.	How to ventilate cross-passages to provide adequate climatic conditions for maintenance personal and equipment?	x	x	x		x	x		x
4.	How to provide protection of sensible equipment against adverse climatic conditions?	x	x	x			x		
5.	How to maintain smoke free and moderate conditions in cross-passage and non-incident tube during emergency?				x			x	x

	Design issue concerning cross-passages and others	Operation Mode				Specification Origin			
		Normal	Maintenance	Disturbed	Emergency	Aerodynamics	Climate	Fire safety	Ventilation
6.	How to prevent persons from non-intentionally walking into a tunnel under operation?		x		x	x		x	
7.	How to provide a functional drainage system?	x			x	x	x	x	

Table 3: Design issues for cross-passages, most relevant mode of operation and the origin of the design issue

Table 4 provides design solutions for the questions of Table 3.

	Aspect	Design solution for cross-passages in twin-tube, high-speed rail tunnels
1.	design loads / strength doors walls	Depending on various boundary conditions (tunnel and train geometry, velocity, etc.), the pressures might fluctuate by +/-10 kPa in one tube and might differ between the two single-track tubes by more than 20 kPa. Several load alternations might appear during one single train passage. The pressure fluctuations must be taken into account by the civil design (cross-passage walls, drainage system) and equipment (doors, cabinets, air-conditioning units).
2.	doors for cross-passages	Since escape routes must be usable in both directions and the wind-loads or ventilation forces might become significant (doors might bang), swing doors may not be adequate, particularly, if they are not equipped with a mechanical gear. Comparatively good features show sliding doors; however, these might need additional excavation for niches. Weather the doors should be motorised and remotely controlled or not depends on boundary conditions such as the ventilation concept, alarm and rescue concept and the force required to open the doors. 
3.	ventilation of cross-passage	In order to prevent strong fluctuations of the air movement in the cross-passages, one side of a cross-passage should be airtight during normal operation. The fresh air supply and the discharge of air from/to only one tube are advantageous. This avoids effects such as internal re-circulation of air, strong pressure fluctuations on either fans or passive mechanical elements for air exchange. Air exchange should be set up with the tube of more favourite climate. Air is taken from the tube that is cooler or less polluted at that location of the tunnel, i.e. in the middle of the tunnel, the tube is changed from which air is taken (see Figure 9).
4.	sensible equipment	In general, as much as possible of the sensible equipment should be installed outside the tunnel. Since fresh air for a cross-passage can often only be supplied from the rail tunnel, the air is often too polluted, warm and/or humid for the equipment. Therefore, the equipment needs protection. Limiting the air-conditioned space to a minimum is most cost saving. Highly sealed and pressure resistant cabinets are often more reasonable than rooms with air-conditioning. Plug connections allow a quick installation and an exchange of the cabinet. Plug-and-socket connexions are preferably mounted inside the cabinet where they are well protected. 

	Aspect	Design solution for cross-passages in twin-tube, high-speed rail tunnels
5.	smoke free / moderate climate in cross-passages	Figure 14 and Figure 15 show general schemes of ventilating cross-passages during an emergency. These principles allow keeping the cross-passages free from smoke upon opening of the doors. In order to allow a minimum flow of air for smoke removal even when doors are closed, dampers might be necessary to allow a minimum air exchange in the cross-passage. Alternatively, remotely controlled doors, which allow partial opening, might be necessary. Even with fire resistant doors, heat might build up in a cross-section. This endangers equipment servicing the non-incident tube. This is another reason why a minimum air exchange is necessary in a cross-section.
6.	prevention of non-intentionally walking in tunnel	At any time during an emergency, doors should allow a free passage. Commonly, cross-passages cannot serve as a waiting room but as a passageway. However, during an emergency shortly after an alarm or during maintenance by mistake, it is possible to run into the parallel tunnel with high-speed trains passing. To avoid accidents in such situations, in some tunnels, doors are locked when trains approach. Inherently, this safety measure might fail leading to doors, which cannot be opened when necessary. Authorities have different opinions on this issue. 
7.	drainage system	Manhole covers of the drainage system or, possibly, cable tubes should be locked. The drainage systems should not lead to an aerodynamic connection between the single tubes, i.e. the drainage system should be decoupled. The drainage system of the cross-passage could be connected to one tube only in order to eliminate an aerodynamic coupling.

Table 4: Design solutions for the questions of Table 3

5 SUMMARY

In the past, single-tube, double-track tunnels were most common for short and long tunnels. Twin-tube tunnels were mainly used for very long distances. Currently, twin-tube is preferred for increasingly shorter tunnel length because of several safety features. Currently, most modern long, high-speed tunnels are planned as twin-tube system. Compared to single tube, double-track tunnels, high-speed twin-tube tunnels might cause more extreme aerodynamic conditions (pressure deviation from normal pressure, pressure differences, pressure fluctuations in time, micro-pressure waves) and lead to increased traction power requirements. Unidirectional traffic in twin-tube tunnels improves the air-exchange and quality of the tunnel climate. New rail tunnels, especially for mixed traffic, are mostly equipped with mechanical ventilation. Twin-tube tunnels allow for a better utilization of the mechanical ventilation and in combination with cross-passages a significant reduction of the escape distance during fire to a smoke-free haven. Better access for rescue and fire fighting operation are provided due to cross-passages. The design of cross passages needs to fulfil various functional requirements. High-quality mechanical equipment such as cross-passage doors or cabinets for electrical equipment are necessary to withstand the climatic conditions in a tunnel. A reliable ventilation system (passive or mechanical) is often required.

6 REFERENCES

[1] UIC, "Arrangements to ensure the technical compatibility of high speed trains", UIC leaflet 660, 2nd edition, 2002

[2] Deutsche Bahn, "Eisenbahntunnel planen, bauen und instand halten", Regelwerk D853, August 2003

APPENDIX A: EXAMPLE FOR CONSEQUENCES OF SYSTEM CHANGE

The difference between twin and single-tube tunnels is illustrated for 2 hypothetical tunnel systems. Table 5 characterizes the rail tunnels investigated.

	Aspect	Parameter
Tunnel	length	10 km tunnel
	free cross-sectional area	double-track: 70 m^2; single-track: 45 m^2
	cross passage distance	every 330 m
	tunnel lining temperature	25 °C
	temperature at portals	12 °C
	yearly temperature fluctuations of ambient temperature	10 °C
Trains	train velocity	250 km/h
	train	ICE3, 400 m long,
	frequency of trains	each direction 4 trains/h
	for the purpose of illustration two trains are passing each other in the single-tube tunnel	after 35 min
	Underground heat	2 years after operation

Table 5: Specification for a comparison of hypothetical single- and twin-tube rail tunnels

One-dimensional simulations were preformed based on the boundary conditions as described in Figure 6. Computer codes simulated the air velocity, pressure fluctuations, thermodynamics and traction requirements in a twin-tube, single-track and a single-tube, double-track tunnel.

	Parameter	Double-tube, single-track; 45 m^2; cross passage every 330 m	Single-tube double-track 70 m^2	
		Single trains	Single trains	Passing trains
1.	theoretical max. escape distance to protected ambient	165 m	5'000 m	
2.	mean air velocity	3.09 m/s	0 m/s	0.78 m/s
3.	max. air velocity away from train	16 m/s	10 m/s	22 m/s (1 peak)
4.	design peak velocity of air during train passage [2]	218 km/h	140 km/h	
5.	max. positive pressure deviation from normal pressure	4.77 kPa	2.79 kPa	4.95 kPa
6.	max. negative pressure deviation from normal pressure	-4.76 kPa	-2.68 kPa	-4.28 kPa
7.	max. pressure change in 3 s interval; no sealing of trains	777 Pa	432 Pa	646 Pa
8.	max. traction power	12.78 MW	10.26 MW	13 MW (1 peak)
9.	max. temperature – Summer	33 °C	32.4 °C	
10.	mean temperature - Summer	29.7 °C	30.7 °C	
11.	min. temperature – Winter	5.3 °C	9.4 °C	
12.	mean temperature – Winter	20.4 °C	21.9 °C	

Table 6: Comparison of 2 hypothetical single and twin-tube tunnels (10 km) with trains (250 km/h, 400 m long ICE3 train); calculations conducted with THERMOTUN (Prof. Vardy; United Kingdom) and THERMO (HBI Haerter Ltd.; Switzerland)

APPENDIX B: EXAMPLES OF CURRENT EUROPEAN RAIL TUNNEL PROJECTS

	Rail tunnel	Length / system	Major ventilation measures
1.	Alpine Base Tunnels at Brenner, Gotthard, Loetschberg, Lyon-Turin (Austria, France, Italy, Switzerland)	35 to 57 km 2 x single track for mixed traffic	Simultaneous air supply and extraction by ventilation stations; fully redundant ventilation; Ventilation objective: Critical velocity in incident tube; smoke-free of cross-passage and non-incident tube.
2.	Ceneri Base Tunnel (Switzerland)	15 km 2 x single track for mixed traffic	Simultaneous air supply and extraction by ventilation stations; fully redundant ventilation; Ventilation objective: Critical velocity in incident tube up to fires of freight trains of 250 MW
3.	Groenehart Tunnel (The Netherlands)	7 km single tube with perforated separation wall for passenger high-speed trains only	Longitudinal ventilation by jet fans; ventilated emergency exits; Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 40 MW; no smoke dispersion through doors
4.	Guadarrama Tunnel (Spain)	28 km 2 x single track for passenger high-speed trains only	Fresh air supply and smoke extraction by fan stations at the portals on both tunnel sides; doors for closure of rail at all four portals; Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 50 MW; no smoke penetration in cross-passages
5.	Katzenbergtunnel (Germany)	10 km 2 x single track for mixed traffic	No mechanical ventilation; 2 shafts near highest point for natural ventilation and smoke extraction; Ventilation objective: Smoke extraction with thermal buoyancy effect
6.	Le Perthus Tunnel (France-Spain)	8 km 2 x single track for mixed traffic	Jet fans in rail tunnels; Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 100 MW; no smoke penetration in cross-passages
7.	Stoerebaelt Tunnel (Denmark)	8 km 2 x single track for mixed traffic	Jet fans in rail tunnels; Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 100 MW; no smoke penetration in cross-passages
8.	Wienerwald Tunnel (Austria)	11 km 2 x single track for mixed traffic	Smoke-control by fan stations in rail tunnel; Ventilation objective: Critical velocity in certain parts of tunnels for passenger trains of up to 20 MW

Table 7: Examples of current European rail tunnel projects at the planning or construction phase (major deviations due to progress in design of projects possible)

Authors Biography

Peter Reinke studied mechanical engineering at the Technical University of Braunschweig (Germany) and the University of Waterloo (Canada). His Ph.D.-research on the explosion of superheated liquids at the Swiss Federal Institute of Technology in Zurich (Switzerland) became awarded with the medal of excellence. In 1997, Dr. Reinke joined HBI Haerter Ltd. (www.hbi.ch). He worked on various international rail and metro tunnel projects. Among his activities in aerodynamics, climate, mechanical equipment, ventilation and safety are various challenging projects such the longest rail tunnel in the world (Gotthard base tunnel), or tunnels for the innovative high-speed magnetic levitation train line in Munich.

Stig Ravn obtained his B.Sc. in Mechanical Engineering from the Engineering College of Copenhagen in 2000 specialising in thermodynamics and mathematical modelling. The same year he started to work for INTABB (the M&E contractor for the Copenhagen Metro) as project engineer designing and equipping the tunnel ventilation for the Copenhagen Metro. In 2002, he joined HBI Haerter Ltd. (www.hbi.ch) working as consultant engineer for various international tunnel projects including metro, rail and road tunnels.

Certificate

The authors certify that the paper titled "Twin-tube, single-track high-speed rail tunnels and consequences for aerodynamics, climate, equipment and ventilation" and submitted for consideration for Conference on "Tunnelling Asia' 2004" to be held in New Delhi form 14-17 December 2004 is in original and has not been published or presented at any other forum.

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