SELF RESCUE IN RAILWAY TUNNELS - EVACUATION SIMULATION RESULTS

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ABSTRACT

Evacuation simulations were performed to analyse the sequence of events of organised self-rescue campaigns and to identify the relevant influencing factors. Two different tunnel systems – a twin-bore tunnel with cross-passages and a twin-track tunnel with emergency exits – were used as examples to determine and compare evacuation times for pre-selected scenarios. These investigations helped to bring the strong points and the weak points of the tunnel systems, the procedures adopted, and the behaviour of the persons involved to light.

1. RELEVANCE OF SELF-RESCUE IN RAILWAY TUNNELS

In the past, it was long unclear, which targets should be prioritised and which topics should be focused on with respect to the safety design of railway tunnels. On the one hand, designers were confronted with a lack of experience, as accidents in railway tunnels would only occur very infrequently, and on the other hand there was a lack of practice in performing systematic safety analyses. All this changed drastically in the 1990ies. At this point in time, several accidents involving fire in railway tunnels (e.g. the Zurich Hirschengraben Tunnel in 1991, the Channel Tunnel in 1996) as well as in road tunnels (the Mount Blanc Tunnel in 1999, the Tauern Tunnel in 1999, and the Gotthard Tunnel in 2001) occurred which dramatically illustrated the potential hazards and subsequently prompted a dynamic development in the field of tunnel safety. The planning of numerous new tunnels furthermore forced designers to intensively discuss safety questions prior to any construction works.

Today Austria, like many other European countries, has a clear and largely undisputed ranking of priorities with respect to safety targets:

- Prevent accidents
- Minimize the extent of damage of accidents
- Ensure a fair chance for self rescue
- Provide good conditions for assisted rescue

If a comparison is made between the efficiency of self rescue and assisted rescue, both the practical experience gained with fire accidents and the results obtained from risk analyses clearly tip the scales in favour of self rescue. With fires, it's the first few minutes, which decide about the actual rescue chances. Outside help normally tends to come too late. It is for this reason that the focus of attention is on self rescue.

With self rescue, it is the prime objective of the persons affected by a fire accident to reach a so-called "safe area" as fast as possible. Such a "safe area" may either be an emergency exit leading to the open air, or a cross-passage leading to a second tunnel tube, which is unaffected by the accident including possibly resulting consequences (fire).
With respect to this prime objective, there is a general agreement both in Austria as well as in other European countries. Yet there is no agreement when it comes to details, e.g. the maximum admissible distance to be observed between emergency exits or cross-passages. In

this context it is often overlooked that the decisive criterion is not the distance to be covered, but the time needed until a safe area is reached.

If one now looks into the special case of “railway tunnels”, where a great number of people try to escape to a safe area at the same time, even a rough analysis reveals that the distance between the emergency exits is only one out of many influencing factors, determining the time required for passengers and train staff to reach a safe area. It is the aim of this paper to identify and analyse these influencing factors. For this aim to be achieved, a comparison between the following two scenarios was made:

- two single-track tunnels featuring two separate running tunnels and cross-passages (twin-bore tunnel)
- a conventional railway tunnel featuring only one tube with two tracks and emergency exits (twin-track tunnel)

This paper is based on the results of a computerized evacuation simulation, which – on behalf of HL-AG - was performed for the Wienerwald Tunnel as well as for two other tunnels in the Perschling valley.

2. BASIS FOR EVACUATION SIMULATION MODEL

2.1. Procedures to be Adopted for Self Rescue

The rescue concept starts from the following basic assumptions, which are identical with the standards, which in recent years have been developed by the Austrian Federal Railways for self-rescue procedures to be adopted in tunnels. At present, train attendants receive regular training for self-rescue campaigns in tunnels.

- If a fire is detected while a passenger train is travelling through a tunnel, the affected train will first try to leave the tunnel.
- However, if the train comes to a halt inside the tunnel, the train attendant will have to make a decision after investigating the situation on site and after communicating with the traffic control centre
  - whether to evacuate the train
  - how to evacuate the train

  The train attendant will subsequently have to inform the passengers over the train’s loudspeaker system and the traffic control centre over the train radio.
- The traffic control centre will have to inform the fire brigade and will have to issue the necessary instructions for any subsequent or oncoming trains (stopping all train traffic and vacating the tunnel). After clearance has been given for the second track, the train attendant will have to initiate the evacuation of the passengers. They will have to leave the train and walk towards the nearest accessible cross-passage (in the twin-bore tunnel) or the nearest emergency exit (in the twin-track tunnel).
- The passengers will have to leave the affected tunnel bore through cross-passages or emergency exits to reach a safe area.

These steps are independent of whether the train is in a twin-track tunnel or in a twin-bore tunnel. In both cases there are emergency exits, which lead to a safe area, and the evacuation can only be initiated after all train traffic has been stopped.

2.2. Evacuation Simulation Model

For the simulation, the BuildingEXODUS 3.0 software was used. BuildingEXODUS is an evacuation model for the built environment that can be used for evaluating the emergency and non-emergency movement and behaviour of people. BuildingEXODUS enables the analysis of complex people-people, people-structures and people-environment interactions.

The three submodels of the software are:

- Movement:
  Controls the physical movement of individual occupants from their current position to the most suitable neighbouring location, or supervises the waiting period if such a location does not exist. The movement may involve such behaviour as overtaking, side-stepping or other evasive actions.
- Behaviour:
  Determines an individual's response to the current prevailing situation on the basis of personal attributes.
- Occupant:
  Describes an individual as a collection of defining attributes and variables such as gender, age, max. running speed, max. walking speed, response time, agility, etc.

2.3. Infrastructure

2.3.1 Twin-Bore Tunnel

Tunnel system: two parallel running tunnels with one track and cross-passages

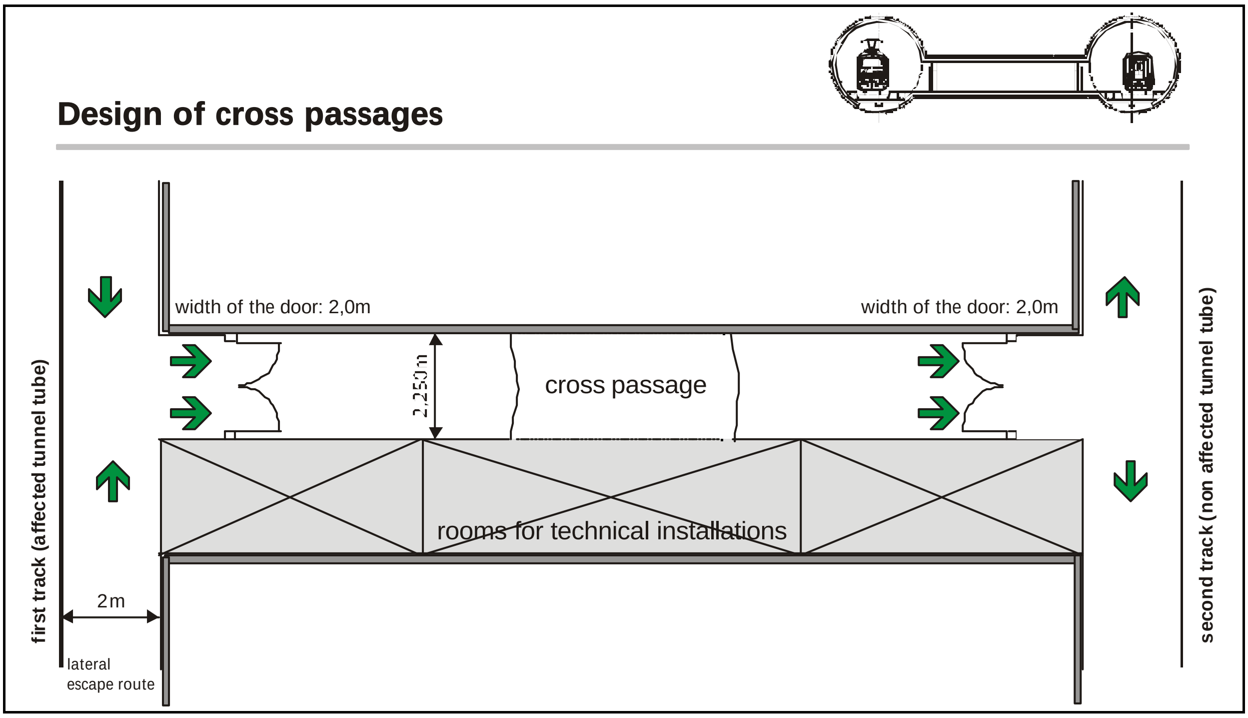

Figure 1: Twin-bore tunnel - design of tunnel system and cross-passages

Width of lateral escape route in running tunnel:	approx. 2 m
Distance between cross-passages:	500 m
Width of cross-passage doors:	2.0 m
Length / width of cross-passages:	approx. 20 m / 2.25 m

2.3.2 Twin-Track-Tunnel

Tunnel system: single-bore, twin-track tunnel with emergency exits with short stairway to the open air

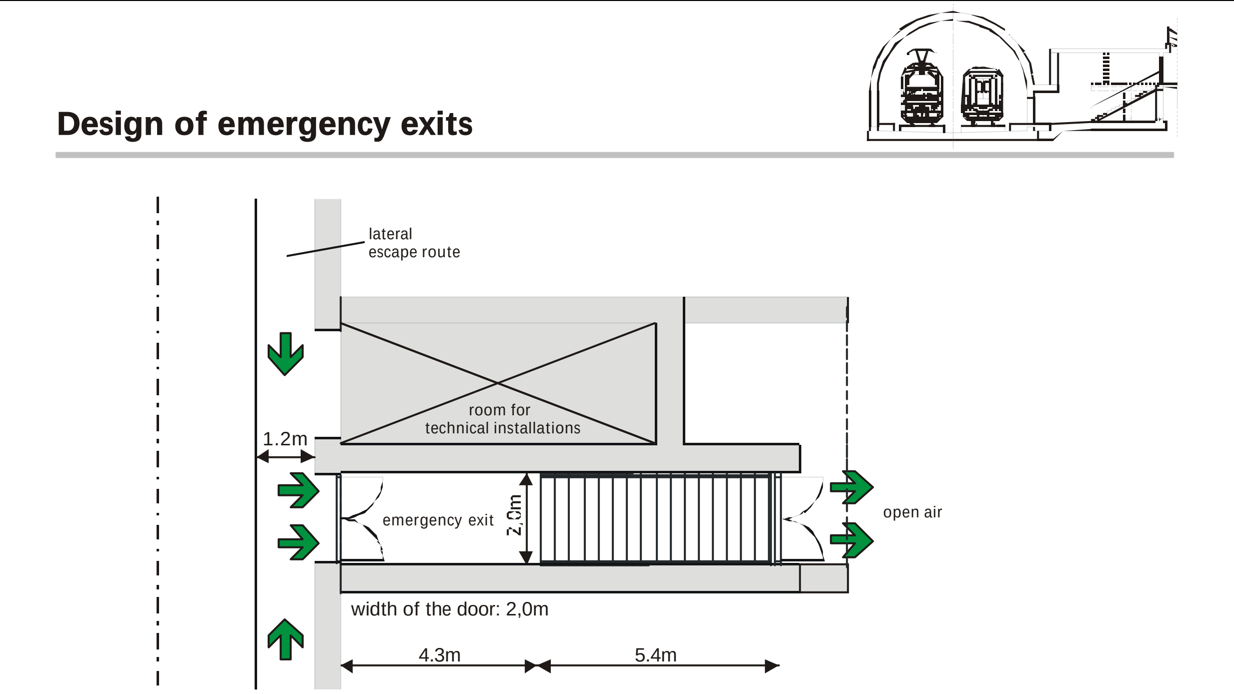

Figure 2: Twin-track tunnel – design of tunnel system and emergency exits

Width of lateral escape routes in running tunnel:	1.2
Distance between emergency exits:	500 m
Width of emergency exit doors:	2.0 m
Length / width of stairway:	5,4 m / 2.0 m
Length / width of queuing space in front of stairway:	4.0 m / 2.0 m

For a comparison of the two tunnel systems, an approx. 1000 m long section of each tunnel system with 3 emergency exits was selected. With both tunnel systems it was assumed that in case of a fire, suitable ventilation measures will be adopted for the safe areas to be protected against the ingress of smoke.

2.4. Number of Passengers / Position of Train in Tunnel / Location of Fire in Train

With all scenarios, the investigation focused on a rather busy, standard-length train. This train consists of 10 passenger carriages without compartments (26 m in length) and carries 500 passengers. In the course of a sensitivity analysis, studies were also conducted for higher passenger numbers.

For both tunnel systems, the following two train positions were scrutinized:

- Train stops between two cross-passages
- Train stops so that the cross-passage is halfway between the front end and the rear end of the train

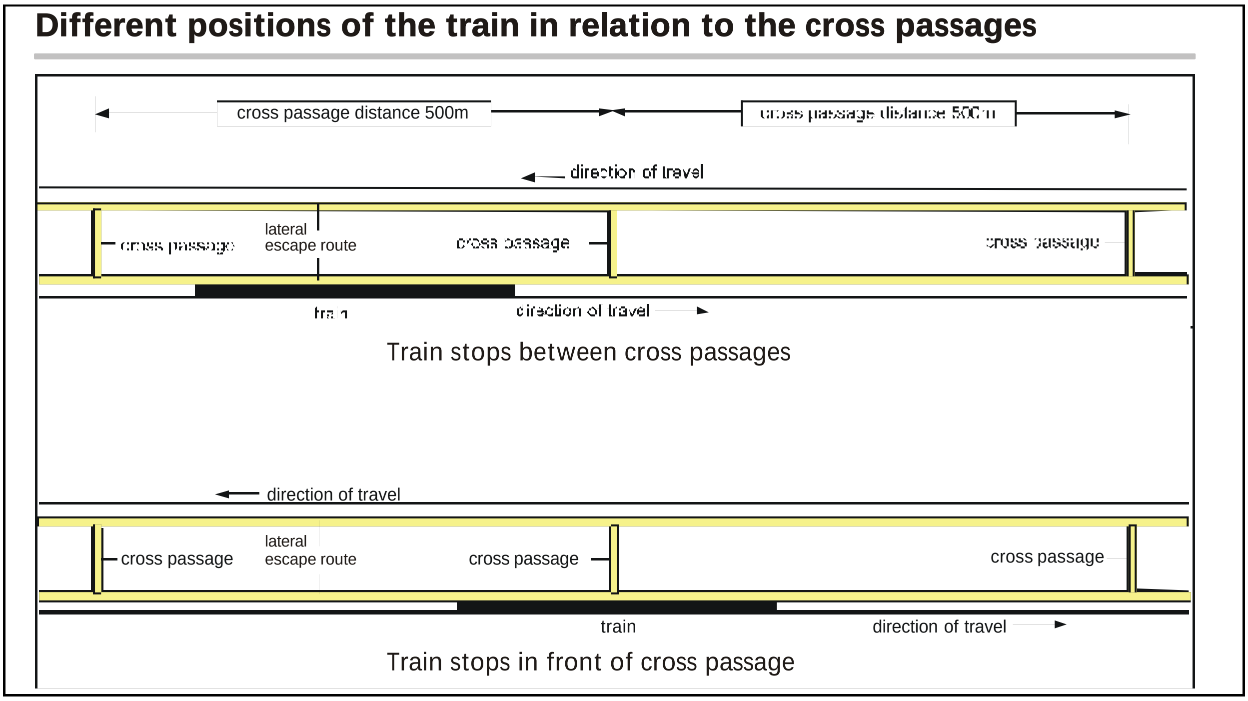

Figure 3: Position of Train in the Twin Bore Tunnel

With the twin-track tunnel, the following differentiation was furthermore made for the "train stops in front of emergency exit" scenario:

- Train stops immediately in front of emergency exit
- Train stops right next to emergency exit (on the opposite track)

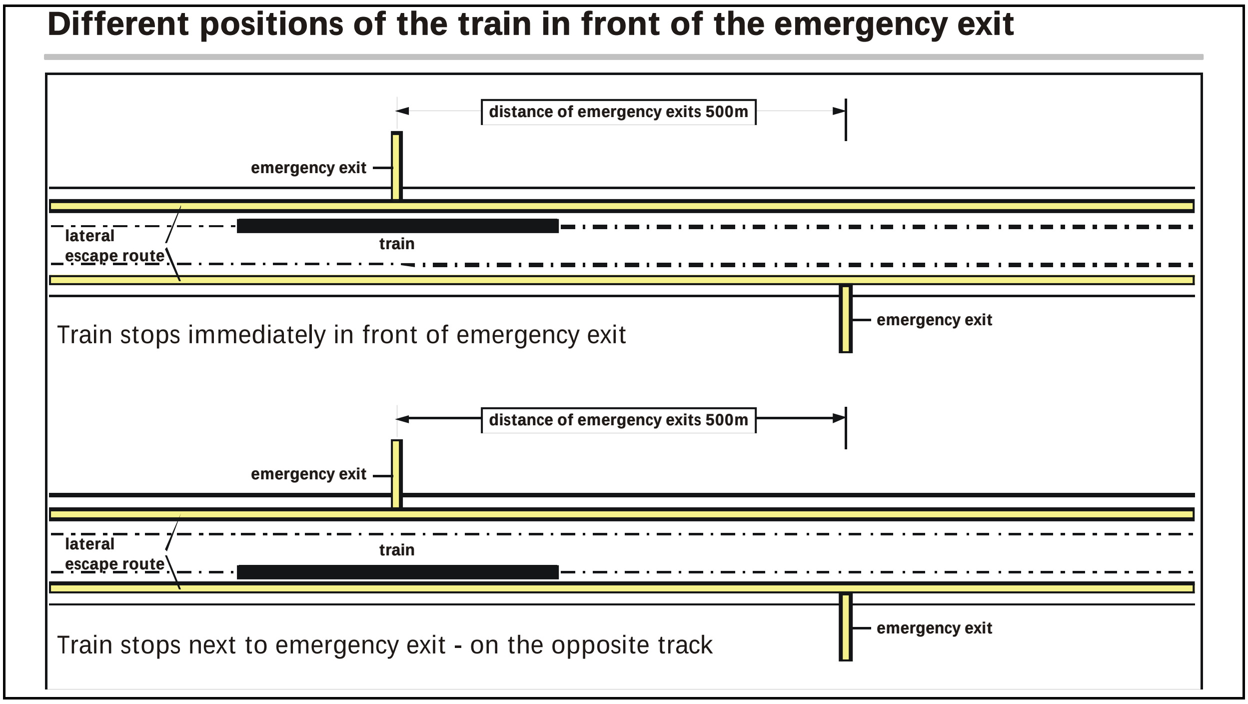

Figure 4: Position of Train in the Twin Track Tunnel

With respect to the location of the fire, investigations were made for positions at the front end, in the middle section, and at the rear end of the train.

2.5. Tunnel Environment and Behaviour of Passengers

For the evacuation, the following boundary conditions were assumed:

- Evacuation without restrictions
- Evacuation with limited visibility on account of incipient smoke build-up in the tunnel

The limited visibility was simulated by progressively reducing the walking speed to 50 % of the initial speed.
Assumed behaviour of people:

- In case of an evacuation without restrictions, it was assumed in the simulation that the people walk to the nearest emergency exit, following the emergency escape signs.
- In case of an evacuation with smoke build-up, it was assumed in accordance with the results of the air flow calculations, that even after the train has come to a halt, an air flow in the direction of travel persists for several minutes inducing the smoke to first spread in the direction of travel. It was furthermore assumed that the fire cannot be passed neither inside nor outside the train. People therefore have to escape on both sides of the fire, away from the fire. Those in front of the source of fire thus have to escape in the smoke-filled tunnel in the direction of air flow.

2.6. Calculation of Total Evacuation Time

The total evacuation time is composed of the following elements:

- Decision time (recognition of danger – coordination with traffic control centre – decision to evacuate the train – instruction to effect self rescue);
  For all scenarios a constant value of 2 minutes was assumed – this value is realistic if the communication sequences are well organised.
- Evacuation time (leaving the carriage – moving away from the danger zone – walking to a safe area, possibly congestion in front of the emergency exit – exit to a safe area) This value was calculated by means of the simulation programme. The results tabled below also contain a decision time of 2 minutes.

3. EVACUATION SEQUENCE – DIFFERENCES BETWEEN TUNNEL SYSTEMS

Prior to any determination of the evacuation times for the individual scenarios, a detailed analysis of the evacuation sequence is required for the different assumptions. This analysis already provides valuable information for the preparation and implementation of a self-rescue campaign and reveals distinct differences between these two tunnel systems:

<u>Twin-bore tunnel:</u>

- The situation at the time of passengers leaving the train is clear and obvious, as is the escape direction (only one sideway; egress only possible on one side of the train; escape to the nearest emergency exit following the escape route signs).
- In the initial self-rescue phase, there is no danger by trains on the neighbouring track.
- The danger of an emergency exit being overlooked due to limited visibility is negligible (all emergency exits are located on one side; clear marking and guidance by handrails possible).
- There is generally a risk of tunnel occupants being endangered by trains on the second track (e.g. in case of communication problems or shortcomings in the preparation of the self-rescue effort), yet only once they enter the 2. tube
- Passengers who have already reached the sideway of the safe tube may literally stand in the way of passengers subsequently seeking to escape through the cross-passages.

Twin-track tunnel:

- The situation at the time of passengers leaving the train is not clear (sideways on both sides; egress on both sides possible; nearest emergency exit may be on either side). Thus there are several options for train occupants to leave the train and to seek refuge, and the optimum option may not be visible at first glance.
- The risk of passengers being endangered by trains on the neighbouring track (e.g. in case of communication problems or shortcomings in the preparation of the self-rescue effort) is imminent immediately upon disembarkation.
- The emergency exits may be located on different sides. Tunnel occupants may - as a result - be obliged to cross tracks or may run the risk of missing an emergency exit on the opposite side due to limited visibility.

4. EVACUATION SIMULATION RESULTS

4.1. Potentials and Limitations of Evacuation Simulations

Evacuation simulations, in principle, start from the assumption of an organised self-rescue campaign, i.e. the evacuation is co-ordinated by the train crew in compliance with existing railway regulations with passengers following their instructions. Yet, in reality this may not always be true, i.e. passengers – or at least some passengers – might behave differently. Evacuation simulations may also be utilized to investigate differences in behaviour; yet this was not the case in this investigation.

Evacuation simulations may be used to study various plausible, yet previously determined behaviour patterns and to reveal possible consequences. This way, weak points in the system, in the organisational procedure, or in the individual behaviour can be identified and suggestions for improvement can be made and evaluated. The experience thus gained may then be used to

- optimise the system and/or the procedure, respectively
- favourably influence the travellers' behaviour by adopting suitable measures.

Evacuation simulations are, however, not suited to predict the travellers' behaviour in a concrete accident situation. The present investigation is definitely not suited to provide a final answer to the myriad of complex questions that circulate around the self-rescue procedure issue, but is intended to raise the sensibility for the multitude of conceivable correlations and to analyse the relevant influencing factors including their mechanisms of action.

The investigation covers scenarios with and without smoke; without smoke to first analyse the relevant influencing variables of the system without hampering environmental effects, and with smoke to determine which additional effects are created by the impact of smoke.

4.2. Results Twin-bore Tunnel

The total evacuation time for the investigated scenarios has been listed in the Table below:

Scenarios	Train between cross-passages	Train in front of cross-passage
without fire	8 min 55 sec	6 min 07 sec
with fire at rear end of train	14 min 57 sec	6 min 43 sec
with fire in middle section of train	10 min 31 sec	21 min 27 sec
with fire at front end of train	12 min 37 sec	6 min 23 sec

On the basis of these results, the following essential conclusions can be drawn.

Scenario without fire:

- Train between cross-passages:
  The decisive influencing factor is the distance between the cross-passages.
- Train immediately in front of cross-passage:
  The decisive influencing factor is the capacity of the cross-passage door.
- The sideway width in the running tunnel is no decisive factor.
- The evacuation time of 500 passengers is shorter with the “train in front of cross-passage” scenario than with the “train between cross-passages” scenario. Yet with growing passenger numbers, the evacuation time for the “train in front of cross-passage” scenario increases considerably, since in contrast to the “train between cross-passages” scenario, there is only one emergency exit.

Scenario with fire:

- The build-up of smoke in the tunnel and the need to take a different escape route due to an unfavourable location of the fire (people will escape away from the fire and will not try to get past the fire) inevitably lead to considerably longer evacuation times.
- Train between cross-passages
  In some scenarios, the emergency exist cannot be reached due to an unfavourable location of the fire and the passengers are forced to head in a different escape direction (longer escape routes and the influence of smoke cause considerable delays)
- Train in front of cross-passage
  Only minor delays are experienced if the fire is situated at the front or the rear end of the train. The most unfavourable situation occurs when the source of the fire is located in the middle section of the train and in the immediate vicinity of a cross-passage preventing people from using this cross-passage and forcing them to proceed to the next cross-passage.

4.3. Results Twin-track Tunnel

Scenarios without fire

Scenarios	Train between emergency exits	Train in front of emergency exit
Standard design emergency exit	9 min 38 sec	9 min 37 sec
Improved design emergency exit		
- wider stairway (2.40 m instead of 2.00 m)	9 min 20 sec	7 min 41 sec
- sufficient queuing space in front of stairway (25 m²)	9 min 23 sec	8 min 22 sec

- Train between emergency exits:
  The decisive influencing factors are the distance between the cross-passages and the stairway capacity
- Train immediately in front of emergency exit:
  The decisive factor is the stairway capacity; there are considerable capacity problems at the emergency exit.

Therefore the following improvements have been investigated:

- Increase of stairway width by 40 cm (an additional walking lane)
  20 % improvement achievable
- Increase of queuing space in front of stairway from 7 m² to 25 m²
  10 % improvement achievable

Both these measures show only little effect if the train comes to a halt between emergency exits (only minor capacity problems, because two emergency exits can be used)

- The sideway width is no decisive factor (although width in twin-track tunnel only 1.2 m compared to 2.0 m in twin-bore tunnel).

Scenarios Train stops next to emergency exit on neighbouring track	Train next to emergency exit
Alternatives of disembarkation: - Egress to neighbouring track - Egress to opposite sideway, Crossing of tracks before / behind train - Egress to opposite sideway, Evacuation to neighbouring emergency exit	 9 min 59 sec 11 min 20 sec 13 min 44 sec

This scenario, which forces passengers to cross the tracks to reach the emergency exit on the opposite side (see figure 4), causes delays independent of the disembarkation alternative ultimately chosen.

- Both alternatives which involve crossing the tracks and using the opposite emergency exit were found to be more favourable than the option of using the neighbouring emergency exit without crossing the tracks
- Yet this effect is reduced in case of rising passenger numbers, due to capacity problems which are experienced if only one emergency exit is used.

<u>Scenarios with fire</u>:

Scenarios	Train between emergency exits	Train in front of emergency exit
without fire (for comparison)	9 min 38 sec	9 min 37 sec
with fire at rear end of train	14 min 46 sec	-
with fire at middle section of train	10 min 36 sec	18 min 45 sec
with fire at front end of train	14 min 59 sec	9 min 37 sec

- Train between emergency exits
  The main influencing factors and the simulation results are very similar to those of the twin-bore tunnel. The longer evacuation times in the “fire at front end of the train” scenario can be explained by the necessity of having to cross the tracks to reach the emergency exit
- Train in front of emergency exit
  The most unfavourable situation occurs when the source of the fire is located in the immediate vicinity of a cross-passage (i.e. cross-passage can not be used and tunnel occupants will have to proceed to the next emergency exit)
- The impact of an insufficient stairway capacity continues to persist even in case of a delayed evacuation as a result of limited visibility due to smoke build-up, which explains the considerably longer evacuation times (as compared to the twin-bore tunnel).

5. CONCLUSIONS

- The investigation results reveal that in a modern railway tunnel with emergency exits at intervals of 500 m, a self-rescue of approx. 500 passengers is possible in a period of approx. 6-15 minutes. This is even true in case of limited visibility due to smoke build-up. Only under very adverse conditions, may self-rescue efforts require up to 20 minutes.
- The main influencing factors and the simulation results tend to be very similar with twin-bore tunnels with cross-passages and with twin-track tunnels with emergency exits.
- Yet, decisive differences are discernable in the following domains:
  - The decision-making process before and during an evacuation procedure as well as the evacuation sequence, tend to be more complex in a twin-track tunnel than in a twin-bore tunnel.
  - With emergency exits featuring stairways in a twin-track tunnel, the stairway capacity decisively influences the evacuation time.
- In case of a fire, the worst-case scenarios are those in which the location of a fire blocks the access to a favourably sited emergency exit forcing passengers and train staff to take a detour.
- The results clearly show that the evacuation time is substantially influenced by the position of the train and/or the position of the fire inside the train. It should thus be checked whether in case of an emergency stop, the position of the train in relation to the emergency exit can be influenced in a favourable way and if so which pre-conditions and which information would then be required.

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