Emergency Scenarios for Tunnels and Underground Stations in Public Transport

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ABSTRACT
The phase from the design to the operation of tunnels for railbound public transportation systems proves to be extremely protracted in practice. This is due to the necessary approval procedures and extremely different appraisals pertaining to safety for instance. The design phase can be appreciably reduced if a standard emergency scenario is presented, for which a suitable safety concept must be available. Experts then decide on the case of fire as a standard scenario from possible emergency scenarios by dint of which the required safety considerations are to be carried out for new structures so that a standard basis for planning is created in Germany. The principal approach is shown for example for designing underground stations so that persons can rescue themselves and be rescued through establishing short evacuation periods and long smoke proliferation periods.

Keywords: smoke build-up time, evacuation time, walking speed, self rescue, assisted rescue, smoke protection measures

1. EMERGENCY SITUATIONS IN TUNNELS AND CHOOSING A STANDARD EMERGENCY SCENARIO
Essentially a distinction has to be drawn between an operational breakdown and an emergency. When breakdowns occur there is no danger for persons but normal services have been interrupted. They can be triggered by various factors. In such a case, passengers are only affected by e.g. delays in travelling times.
Emergency situations always involve potential danger for people – as can be e.g. the case during derailments, collisions or fires. Defective operating equipment can also lead to emergency situations should this result in accidents resulting in persons being injured or worse or fires occurring. An emergency situation always involves people being endangered. Examples for the causes of emergency situations are:
(1) Vehicles
   (a) derailment
   (b) collision with obstruction
   (c) crash with another train/accident resulting from collision
   (d) vehicle fire
(2) Station
   (a) defective operating equipment
   (b) cable fire
   (c) casualties/suicide
   (d) escalator fire
   (e) fire in sales outlets and/or service premises
It is essentially extremely difficult to estimate the effects and possibilities to provide protection in conjunction with attacks carried out by terrorists in Public Commuter Transportation tunnels. As attacks of this nature do not represent a specific problem for tunnels, they are disregarded in the scope of further investigations.
If one compares a case of emergency involving fire and a large proportion of passengers, who are no longer capable of saving themselves with a case without fire, then the scenario with fire has always to be assessed as more unfavourable and more critical. During a fire incident after all, injured persons must be able to escape or be rescued in a very short limited period in order to preclude smoke poisoning and burns as far as possible.

2. VEHICLE FIRE IN SCENARIO
Experience shows that fires in underground, suburban and urban rolling stock occur very seldom. During the last 40 years in Germany for instance, no resultant deaths have been recorded and the number of injured is extremely small [1]. Fires can be caused e.g. by defects in the vehicle electronics system and by arson. Fires in modern rolling stock are self-extinguishing – except when exposed to an outside source of energy for some length of time or if criminals plant substances designed to accelerate combustion. Once ignition occurs the further course of the fire depends on the amount of available oxygen, the quantity of combustible materials in the vehicle and their inflammability (Fig. 1).

Public commuter transportation company vehicles are not all equipped in the same way to resist fire on account of their long service life (in some cases up to around 30 or 40 years). DIN 5510 [2] has applied for preventive fire protection in track-bound vehicles since 1988. All rolling stock built since then must comply with this norm in Germany. Older vehicles are refitted during regular maintenance checks (e.g. seats, cables) so that these vehicles, by and large, now comply with DIN 5510 [2].

3. THE SPREADING OF SMOKE IN UNDERGROUND STATIONS
3.1 Permissible smoke
The hot smoke gases, which stream out of the coach, largely spread themselves in layers at the tunnel roof or the ceiling of the underground station, providing that the air flow in the tunnel’s longitudinal direction is low. Existing eddies and back-flows of the hot smoke gases lead to an undefined border area between the upper hot gas layer and the cooler cold gas layer located below it. This cold gas layer is also known as the low smoke layer.

People cannot survive in the hot gas layer without additional protective measures. The low smoke layer (cold gas layer) must possess a sufficient thickness so that persons can survive within it. Furthermore, the temperature prevailing there must be acceptable for persons (T<50°C), there must be sufficient oxygen (<14 Vol.-%) and the toxic substance concentrations in this layer must not exceed the permissible limit values (e.g. CO < 500 ppm). Furthermore, it must be shown that visibility within this low smoke layer amounts to at least approx. 10 m so that people trying to escape can orientate.
themselves and do not panic. This visibility is possible providing the surrounding lighting amounts to around 40 lux and the optical density is approx. 0.13 m$^{-1}$ at the most [1]. When the fire starts the visibility is far greater and diminishes correspondingly first as the fire progresses. It is no longer possible for persons in underground stations to save themselves if the facility contains an excessive amount of smoke. This is the case when the thickness of the low smoke layer (cold gas layer) above platform level is less than 2.5 m [1] – or, however, the optical density in the low smoke layer exceeds 0.13 m$^{-1}$.

The time span until one of the above-mentioned limit values is attained is known as the smoke build-up time. Smoke build-up times have always to be longer than the corresponding evacuation periods for the stations.

The fire service demands that during the self-rescue phase or rescue by a third party an on average approx. 2.5 m to approx. 1.5 m thick low smoke layer is retained above platform level with sufficient visibility for a duration of at least 15 minutes or 30 minutes from the fire starting (Fig. 2). Through these demands, it is intended to ensure that

1. persons are able to escape during the self-rescue phase without outside help unhampered providing there is sufficient visibility and are not harmed by toxic gas concentrations or high temperature

2. those requiring attention from the emergency services during the third-party rescue phase such as e.g. disabled persons or those under shock are able to receive sufficient clean air to breathe and can be rescued by the fire brigade.

As far as possible stations should be designed in such a way that the above-mentioned demands are met.

3.2 Measures designed to restrict smoke spreading

3.2.1 General

Various constructional measures can be undertaken to effectively restrict smoke spreading in underground stations (e.g. smoke curtains, smoke removal shafts). In this way the period of time available for the evacuation of the passengers can be substantially extended.

3.2.2 Smoke curtains

Smoke curtains are applied to ensure that at least for the duration of the self-rescue phase smoke is transferred from the platform to the stairways and in turn, to distribution level. Smoke curtains must allow a clearance height of around 2 m for escaping persons at all entrance/exit areas (Figs 3 and 4). As the thickness of the low smoke layer during the assisted rescue phase can diminish to around 1.5 m, smoke escapes below the curtains so that it can flow to the ground surface via the stairways during this phase.
3.2.3 Smoke removal shafts
Hot smoke gases can be transferred systematically via smoke removal shafts in the underground station ceiling to the ground surface (see also Fig. 3). The shafts can act either naturally through the thermal effect of the smoke gases or can be equipped with a mechanical ventilation unit. Flow technical calculations have to be undertaken to ensure the shafts are designed to best suit the purpose and to establish the most favourable positions for the smoke access openings at any given station. In addition, it must be observed that the access openings for the smoke removal shafts are kept away from streets as far as possible.

![Smoke extraction shaft and smoke retaining curtain (principle)](image)

Figure 3: Smoke extraction shaft and smoke retaining curtain (principle)

3.3 Calculating smoke distribution
Zone and field computational models are made use of to calculate the smoke numerically [4, 5]. Given the same general conditions both models for geometrically homogenous and less irregular spaces provided approximately the same results for important parameters such as e.g. the thickness of the low smoke layer and visibilities. However, a field model is essential if flow conditions have to be investigated chronologically and locally in complex facilities such as the platform level or distribution level taken together or in the route tunnels.

4. EVACUATING STATIONS
4.1 General
In the selected scenario “Vehicle on Fire but still reaches the next station” it is presumed that fire breaks out when the vehicle is travelling through the route tunnel, is discovered after 0.5 minutes by a passenger and reported to the driver 1 minute after it started. However, the vehicle reaches the next station 2 minutes after the fire starts thanks to the emergency brake bridge-over. In the assumed scenario, the driver requires a further minute to investigate the fire incident and sends an additional report to the control centre 3 minutes after the fire began. He calls on the passengers to leave the train immediately at the station.
4.2 Reaction time and walking speed on the platform
Generally a reaction time for the affected passengers must be taken into consideration for evacuation analyses after the alarm is sounded. This can be very different depending on the circumstances. A reaction time of 1 minute was accepted as realistic in conjunction with the assumed vehicle fire in the research programme. Thus the evacuation of the train and the station starts some 4 minutes after the fire starts – including travelling time and investigation time.
Certain persons are bound to react more quickly to the alarm being sounded than others. These persons can more or less select their walking speed at will as the throng of people en route to the stairways is still relatively low.
Individual pedestrians, who are capable of moving freely, attain walking speeds of between 1 and 1.6 m/s depending on their age and state of health. In the research project, an average walking speed of 1 m/s was assumed for calculating the evacuation.

4.3 Congestion in front of the stairways
Gradually a crush of people builds up in front of the stairways depending on the number of persons involved as well as the capacity of the stairs. Those persons located at the foot of the stairs will one after the other be able to reach the distribution level from platform level depending on the actual capacity of the stairs. The longer one has to wait the smaller the crush of people in front of the stairs will become before it finally ceases altogether after all those involved have used the stairs. It can be assumed that a group of people will form in the stairway area leading to the distribution level, who wish to escape into the open.

4.4 Walking speeds on solid stairs
The values that apply to walking speeds of individuals on stairs in salient literature are related to the vertical, inclined or horizontal length of the stairway. This must be considered when comparing various walking speeds on stairs. A walking speed related to the vertical height components of the stairs of 0.25 m/s was selected in accordance with NFPA 130 [6] for solid stairs leading upwards.

4.5 Stair capacity
In the research project [1], a stair capacity for solid stairs leading upwards of 37 persons per minute and a 60 cm wide escapeway was selected for calculating the evacuation times for underground stations.
For the evacuation calculations the following definitions were agreed on for escalators:
(1) Generally speaking escalators are 1 m wide. Nonetheless it was decided to select an escapeway corresponding to a width of 60 cm for an escape situation per escalator. In other words, the evacuation calculations preclude people overtaking one another on escalators. As a result, safety reserves are available through this definition.
(2) It was assumed that the escalators were switched off in the event of fire, in other words the worst possible scenario, although in practice escalators running away from the incident should be kept operating as long as possible – as this consequently speeds up evacuation in general and alleviates the procedure for older or disabled persons.
(3) For the evacuation calculations it was assumed that in each case one escalator was out of commission as it can be the case that escalators are not usable because e.g. elements have been removed on account of maintenance work being carried out.
In general it is assumed that the capacities of the stairs, which lead from the distribution level to the surface, are at least as large as those of the stairs from the platform to the distribution level. In addition, it was also assumed that the persons, who were located in the distribution level when the incident began, had already left it, when the first escaping passengers reached distribution level from platform level. These assumptions preclude a crush of persons at distribution level.
Solid stairs must possess a width of at least 2 m in accordance with the Regulations on the Operation of Tramways (BOStrab) relating to tunnelling [7]. Taking the escapeway width of 60 cm into account, such a stairway possesses three parallel escapeways.
4.6 Decisive number of persons for the evacuation
According to EBA guidelines [8] the maximum number of persons to be considered for evacuating an underground station can be worked out as follows:

\[ P_{\text{max}} = n \times (P_1 + P_2) + P_3 \]

- \( n \): number of tracks at the platform
- \( P_1 \): permissible number of seats for the longest train units stopped at the platform
- \( P_2 \): Permissible number of standing passengers for the longest train units stopped at the platform
- \( P_3 \): Number of persons waiting on the platform corresponding to 30\% of the sum derived from \( P_1 \) and \( P_2 \)

If reliable figures are available from e.g. census or prognoses, then these figures should be utilised instead.

4.7 Determining the evacuation times
It was possible to make use of recognised methods to determine the evacuation times, as e.g.:

2. Calculation methods according to Predtetschenski/Milinski [9]
3. Special programmes to calculate evacuation times in underground transportation facilities such as e.g. Pedgo, BuildingExodus or ASERI

On the basis of the established definitions relating to number of persons, walking speeds and stairways and taking the dimensions of the station into consideration, the walking time on the platform, the overall walking time till the ground surface is reached and all waiting times (e.g. in front of the stairways) are determined for the person, who is the last to leave the platform. Towards this end it is assumed that the escaping passengers distribute themselves more or less uniformly over the stairways in keeping with the available stair capacities (so-called hydraulic flow-off principle). The total walking time and all waiting times are added together for the most unfavourable escape route to establish the decisive evacuation time.

5. COMPARISON OF EVACUATION AND SMOKE TIMES
The smoke build-up time is compared with the evacuation times above the various stairways for each particular station under consideration. Generally speaking the evacuation time must always be shorter than the smoke build-up time. The previously cited fire service requirements must also be observed.

6. SUMMARY
The objective must be to attain low evacuation time and as lengthy smoke times as possible through the constructional measures. Towards this end, the two following methods are available with regard to planning stations:

1. The smoke time can be extended by increasing the clear height of the station (larger smoke storage volume), setting up smoke curtains and smoke removal shafts as well as by the application of mechanical smoke extraction units, should space for the stairways be restricted so that it is not possible to shorten the evacuation time.
2. The evacuation time can be shortened by increasing stair capacities (e.g. more or wider stairs) if e.g. there is not sufficient space for large smoke removal shafts (e.g. for shaft openings on the surface) to extend the smoke build-up time.

As far as assisted rescue is concerned, more far-reaching constructional measures can be necessary (e.g. larger smoke removal shafts).

Planners and safety experts must work together closely from the very beginning of the planning stage. It is their responsibility to determine the number of persons for instance, for a particular station, which should be taken into account for the evacuation calculation. In addition, the fire behaviour of the vehicle (e.g. smoke release rate), walking speeds, stair capacities, escapeway lengths etc. should be established on the basis of the prevailing local conditions.
7. LITERATURE


