Emergency scenarios for public commuter transportation tunnels

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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: mass transit, fire safety concept, evacuation, fire simulation, smoke management, emergency scenario.

1 Approach and objectives

The Regulations on the Construction and Operation of Tramways (BOStrab) apply for the construction and operation of Public Commuter Transportation Tunnels in Germany (with the Federal Railway Operation Ordinance – EBO - codes of practice applying for the S-Bahn or Suburban Rail Systems) including any subsequent guidelines, regulations and the generally recognised technological rules such as e.g. DIN and VDV (Association of German Transport Companies) publications. These form the basis for the safety-technical setup of facilities and vehicles but do not contain any emergency scenarios as the basis
for developing holistic safety concepts for the overall system. The concordance
between the client, transportation companies, supervisory authorities and fire
services that is resultantly essential in any city with tunnels in the past came up
with very different appraisals of the risks during cases of emergency and in
assessing the required rescue measures. This subsequently led to different
accents being placed on the given safety concepts. This is for instance, reflected
in different regulations for zoning procedures, which also contain e.g. technical
appraisals for fire protection and conditions imposed by the local fire service. In
practice the phase from the planning of tunnels until they become operational has
turned out to be extremely complicated on account of the attempts to reach the
required agreement and the very different assessments about the efficacy of
measures.

The planning phase could be considerably shortened if there were to be a
standard emergency scenario, which would require the drawing up of a suitable
safety concept.

Thus the prior objective of the research project “Emergency Scenarios for
Tunnels for rail-bound Public Commuter Transportation (OEPNV) and their
Realisation” was to arrive at a standard scenario after experts had appraised
possible emergency scenarios. This would enable the necessary safety
considerations to be undertaken in future so that it would be possible to come up
with a uniform approach in Germany. In addition, examples of basic procedures
should be listed such as how underground stops should be designed so that
evacuation times can be confined to a minimum and long smoke # periods are
attained.

The result should then be guidelines drawn up on the basis of wide agreement
with all those involved from the fields of planning, construction, approval,
operation and emergency services, which are essentially applied uniformly and
nationwide for Underground and urban rail systems as well as for tunnels for
suburban railways and other rapid transport networks used for regional
transportation.

The research project that is presented here was sponsored by circles belonging
to the Ruhr District cities engaged in building Underground or urban railways
via the German Association of Towns and Cities within the scope of the Urban
Transportation research programme (FOPS) of the Federal Ministry of
Transport, Building and Housing – and carried out by STUVA.

2 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) Stop
   (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 were disregarded in the scope of the above-mentioned research project.

If one compares a case of emergency involving fire and a large proportion of passengers, who are no longer capable of saving themselves with one 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.

As a result of thorough and exhaustive discussions among experts, it was decided to select the emergency incident “Vehicle on Fire but still reaches the next Stop” as the standard scenario. This scenario enables many other possible emergency situations to be covered as well.

3 Vehicle fire in scenario

Experience shows that fires in Underground, suburban and urban rolling stock occur very seldom. During the last 30 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 (Figs 1 and 2).
Figure 1: Rate of energy release versus time taking a vehicle of the Frankfurt metro U2 as an example [5].

Figure 2: Rate of smoke release versus time taking a vehicle of the Frankfurt metro U2 as an example [5].

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. 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].
4 The spreading of smoke in underground stops

4.1 Permissible smoke

The hot smoke gases, which rise at the fire seat, largely spread themselves in layers at the tunnel roof or the ceiling of the underground stop, providing that the air flow in the tunnel’s longitudinal direction is low. Existing eddies and backflows 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 visibility within this 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 [3, 6]. 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 [7] – 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 time. Smoke times have always to be longer than the corresponding evacuation periods for the stops.

The fire service demands that during the self-rescue phase or rescue by a third party an on average approx. 2.5 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. 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
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 air to breathe and can be rescued by the fire brigade.

As far as possible stops should be designed in such a way that the above-mentioned demands of the fire service are fulfilled for the self-rescue and outside rescue phases.
4.2 Measures designed to restrict smoke spreading

4.2.1 General
Various constructional measures can be undertaken to effectively restrict smoke spreading in underground stops (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.

4.2.2 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 (Fig. 3).

![Figure 3: Smoke extraction shaft and smoke retaining curtain (principle).](image)

As the thickness of the low smoke layer during the outside 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.

4.2.3 Smoke removal shafts
Hot smoke gases can be transferred systematically via smoke removal shafts in the underground station ceiling to the ground surface. 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 stop. In addition, it must be observed that the access openings for the smoke removal shafts are kept away from streets as far as possible.
4.3 Calculating smoke distribution

Zone and field computational models are used to calculate the smoke numerically [3, 4, 6, 8, 9]. Given the same general conditions, both models for geometrically homogenous and less irregular spaces provide approximately the same results for important parameters such as 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.

5 Evacuating stations

5.1 General

In the selected scenario “Vehicle on Fire but still reaches the next Stop” 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 stop 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 stop.

5.2 Reaction time and walking speed on the platform

Generally a reaction time for the affected passengers must be considered 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 [10] depending on their age and state of health. In the research project, an average walking speed of 1 m/s corresponding with NFPA 130 [11] was assumed for calculating the evacuation.

5.3 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.

5.4 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 [11] for solid stairs leading upwards.

5.5 Stair capacity

The escapeway width (walking track width) on stairs amounts to 60 cm [12, 13]. In literature depending on the general conditions (e.g. normal/dangerous situation, persons with/without luggage) very different stair capacities of 19 to 46 persons per minute and per escapeway are given (Table 1) [10, 11, 14 – 19].

Table 1: Examples for the capacity of a fixed stairway per track (= 60 cm) for walking upwards.

<table>
<thead>
<tr>
<th>Literature</th>
<th>Persons per minute and track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predtetschenski/Milinski [15]</td>
<td>19 – 45(^1)</td>
</tr>
<tr>
<td>Weidmann [10]</td>
<td>30</td>
</tr>
<tr>
<td>VOEV-Schrift 1.51.1 [16]</td>
<td>35</td>
</tr>
<tr>
<td>Dutch Fire Department [14]</td>
<td>43 – 46</td>
</tr>
</tbody>
</table>

\(^1\) according to space needed per person

In the research project, a stair capacity for solid stairs leading upwards of 37 persons per minute and escapeway after NFPA 130 [11] was selected for calculating the evacuation times for underground stops.

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 upwards 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 [21]. Taking the escapeway width of 60 cm into account, such a stairway possesses three parallel escapeways.

5.6 Decisive number of persons for the evacuation

According to EBA guidelines [22] 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 prognoses, then these can also be utilised.

5.7 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 [15]
3. Special programmes to calculate evacuation times in underground transportation facilities such as e.g. SIMULEX [23], STEPS [24] or ASERI [25]

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.

6 Comparison of evacuation and smoke times

The smoke times are compared with the evacuation times above the various stairways for each particular station under consideration. Generally speaking the evacuation times must always be shorter than the smoke times. The previously cited fire service requirements must also be observed.

(1) The time span allotted for self-rescue can be too short unless constructional fire protection measures are undertaken. If so, additional measures have to be carried out.

(2) In many cases, smoke curtains at the stairways as the sole additional measure do not suffice in order to safeguard the conditions for self-rescue of passengers. The smoke time, however, is substantially extended through the smoke curtains.

(3) Non-endangered self-rescue of passengers is possible if an adequately dimensioned smoke removal shaft for natural extraction or for mechanical extraction in complicated cases is provided in addition to the smoke curtains.

7 Summary

The objective must be to attain low evacuation times 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 size of the stop (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 time.

As far as third-party 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 stop, 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.

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