SMOKE AND HEAT EXTRACTION
IN UNDERGROUND STATIONS

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INTRODUCTION

Fire safety engineering in underground stations is of high public interest as metro networks are extended and became a major transportation system in the growing cities world wide. The nature of an underground station poses a challenge to fire safety due to the fact that occupants and thermally driven flows move simultaneously towards the surface. Especially existing structures are in general very narrow, which results in limited possibilities for mechanical smoke and heat extraction systems. In these cases, punctual measures may be of interest. These challenges are addressed by the research project OPRHEUS[1], which recently has been funded by the German Ministry of Education and Research. The main work packages are: conduction of laboratory and full-scale experiments, numerical and physical modelling, and inter-organisational crisis management. This contribution outlines a methodological study on the analysis of different system variants and its combinations with respect to the self rescue phase. It is based on numerical simulations using FDS. The following sub-sections give a brief outline of the investigated metro station, the extraction systems and the underground climate model that has been taken into account.

Underground Station

The target underground station is artificial. Its generic characteristics have been derived form field studies concerning dozens of stations located in Germany. It has a single platform located in between two tracks. Two staircases connect the platform's ends to the surface as shown in Figure 1. The whole structure has an extend of about 120 m × 20 m × 12 m. The ceiling height above the platform accounts to 3.6 m, which is a rather typical height for older stations. Furthermore, the lintels above the staircases serve as static smoke curtains, which have a height of 2.4 m above the platform.

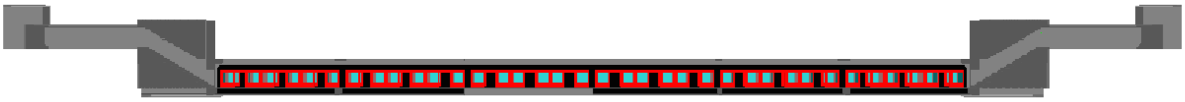

Figure 1: Scematic outline of the underground station.

Underground Climate

Underground stations have very special climatic conditions. It is often assumed that airflows are solely induced by the piston effect caused by moving trains. However, long-term measurements in a couple of cities revealed non-trivial airflow characteristics depending on a multitude of circumstances[2,3]. In particular, it has been found that the airflow is strongly driven by the vertical temperature differences between underground and surface. Additionally, the measurements prove that constant airflows are formed within a few minutes once the train service is stopped. Especially during the fire development, the consideration of airflow may obviously influence the smoke dynamics. As this phase is a part of the the occupant's self-rescue, it appears to be reasonable to examine possible interactions in more detail. Thus, we use the data of long-term climate measurements to derive representative initial and boundary conditions to be incorporated in the CFD-Simulations. Based on the findings presented by Schröder et al.[4], the continuous sampling of temperatures, has been reduced to the consideration of characteristic winter and summer conditions. To ensure comparability, a third set with default conditions has been introduced as well.

Smoke Extraction Systems

The presented study relies on three different methods of mechanical smoke extraction. Method CI (ceiling inlets) represents the classical straightforward approach consisting of inlet openings positioned along the ceiling of the platform level as shown in Figure 2(a). The volume flow of the trial design accounts to 600 000 m^3/h and has been determined by using hand calculation methods. It is evenly distributed over an array of the twelve inlets. In addition to method CI, two alternative and more punctual methods have been investigated. Method SI (staircase inlets) consists of inlets that are placed in the lintels above the two staircases, see Figure 2(b). The volume flow has been set to approximately 30 000 m^3/h. Finally, method SO (staircase outlets) includes outlet openings that are supposed to flush the staircases in direction of the platform level (Figure 2(c)). For that purpose, a volume flow of 90 000 m^3/h has been specified.

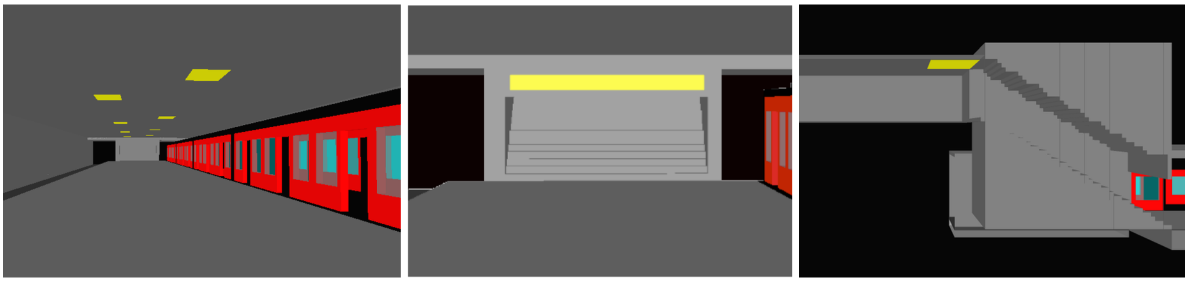
(a) Method CI: Inlet openings distributed over the ceiling (b) Method SI: Inlet opening protecting the staircase (c) Method SO: Outlet opening flushing the staircase

Figure 2: Overview about the examined smoke extraction methods. The light yellow areas illustrate the particular inlets or outlets.

In order to evaluate the interaction between the above-mentioned methods, the latter have been combined to five different smoke extraction strategies. The strategies are summarised in Table 1.

Table 1: Smoke extraction strategies.
CI=ceiling inlets, SI=staircase inlets, SO=staircase outlets

Strategy No.	Method CI	Method SI	Method SO
1	on	off	off
2	on	off	on
3	on	on	off
4	on	on	on
5	off	off	on

METHODOLOGY

The general idea of this contribution is to conduct a sensitivity analysis for a simulation ensemble considering multiple degrees of freedom. In this respect, a full-factorial approach would not be achievable in terms of computational aspects. Thus, we utilise a Latin Hypercube Sampling approach, which has become a popular representative for the application of space-filling designs[5]. In reference to this contribution, the ensemble consists of 150 samples. To cover the the occupant's self rescue out of a rather simple escape route topology, a simulation time of 15 minutes is assumed as sufficient. The domain is subdivided in 24 meshes synchronised by a pure MPI parallelisation. For the spatial discretisation, a uniform gird resolution of $\mathrm{d}x = 20\,\mathrm{cm}$ is chosen in accordance with the characteristic fire diameter as postulated in the FDS User's Guide[6]. Depending on the sampled fire growth and climate conditions, this results in a wall-clock time of approximately 1500 to 2000 core-hours per sample.

Sensitivity Analysis

The parametrisation of the simulation ensemble incorporates the fire growth, three different climatic conditions and the five presented smoke extraction strategies. The sampling range of the fire growth has been chosen in orientation to the findings of the METRO Project[7]. One of the major conclusions presented by Schröder et al.[4] was that the influence of the maximum heat release rate is only marginal in comparison to the fire growth. Thus the maximum heat release rate is fixed at 40 MW The same argumentation yielded the placement of the fire, which is constantly considered almost in the centre of the platform level. A summary of the major data can be found in Table 2.

Table 2: Parameters for the setup of the simulation ensemble

Parameter	**Range**	**Description**
fire simulation		
fire growth α	$0.012\,\mathrm{kW/s^2}$ to $0.188\,\mathrm{kW/s^2}$	uniformly distributed
maximum heat release rate HRR_{max}	40 MW	fixed value
fire location	Carriage No. 3	centre of platform level
climate		
surface temperature T_a	$-10\,^{\circ}\mathrm{C}$ to $30\,^{\circ}\mathrm{C}$	discretely distributed
underground temperature T_u	$10\,^{\circ}\mathrm{C}$ to $20\,^{\circ}\mathrm{C}$	discretely distributed
smoke extraction strategy		
strategy No.	1 to 5	5 combinations

Smoke Spread Analysis

As stated by previous studies[4], the movement of the hot gas layer was described based on the evaluation of the temperature development within the station. However, in this contribution, we rely on the optical conditions in the transition between platform and staircases. For that purpose, soot extinction slices have been converted, processed and – if applicable – computed to times when a particular scenario results in untenable conditions. This condition is based on the evaluation of the local soot density in the middle of each of the staircases. These timings – one per staircase – serve as a measure for quantifying the safety of the escape routes.

RESULTS

Correlation Analysis

Figure 3 illustrates the available save egress time (ASET) at the left and right staircase for all samples. It demonstrates the impact of the fire growth and the smoke extraction strategy. The available times are not symmetrical due to the slightly asymmetrical placement of the fire, towards the right staircase. In the most cases, the SO strategy leads to an ASET which is shorter than the required save egress time (RSET). While all other strategies lead to a save egress time for the left staircase, this is not true for the right one. Here additionally, the strategies CI+SI and CI do not always fulfill the save egress criteria. At the right staircase, the strategies CI and CI+SI significantly outperform the SO strategy. As expected, the straightforward approach CI+SI+SO generally results in a save conditions, which is also true for the CI+SO strategy. The latter shows the efficiency of the classical ceiling extraction (CI) significantly increases with the support of mechanical air inlet (CI+SO). In all unsave cases, the ASET depends nonlinearly on the fire growth.

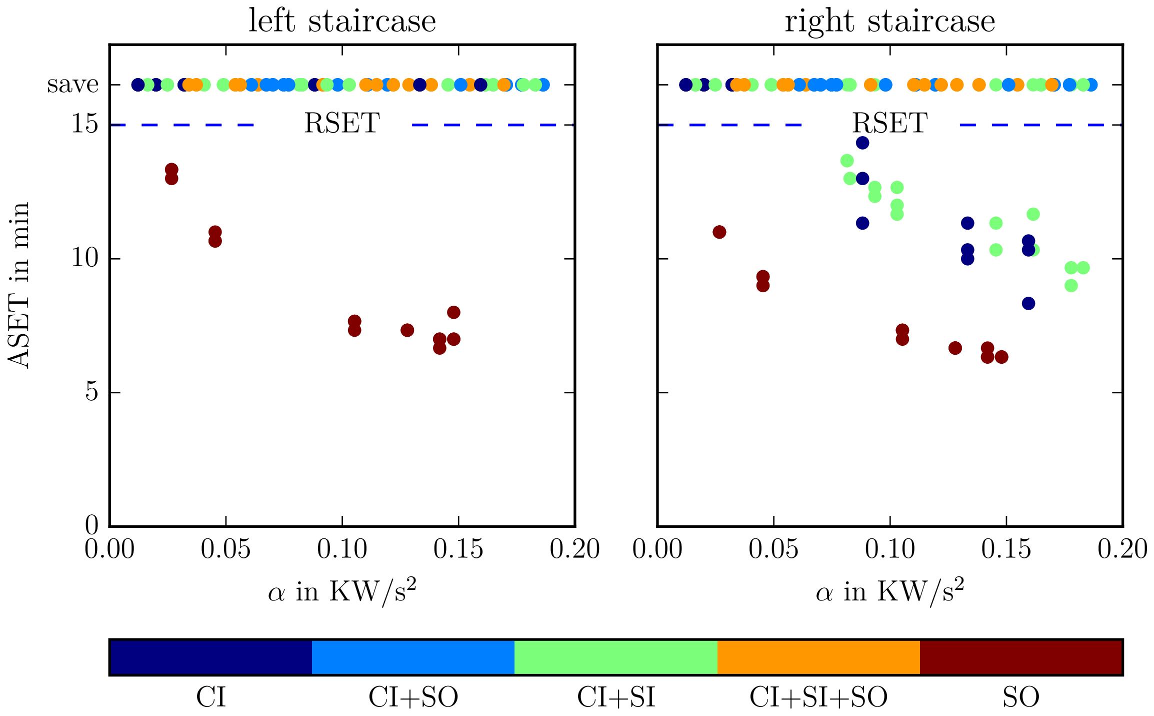

Figure 3: Correlation plots for the ASET as a function of the fire growth α and the smoke extraction strategy for both staircases. An RSET of 15 minutes is assumed here and all scenarios with a longer ASET are marked as save. Color figures available in online version.

Probability Distribution

The comparatively large number of simulations allows for the statistical evaluation of particular performance criteria for each extraction strategy. These information may be of interest e.g. for the conduction of quantitative risk assessments. In terms of smoke spread, the histograms shown in Figure 4 illustrates the probability of the ASET to be within a certain time range, here 0-5, 5-10, and 10-15 minutes, for both staircases. Additionally, the ASET for the case without any mechanical ventilation is presented, following the results from previous studies[4], which in all cases is shorter than the RSET.

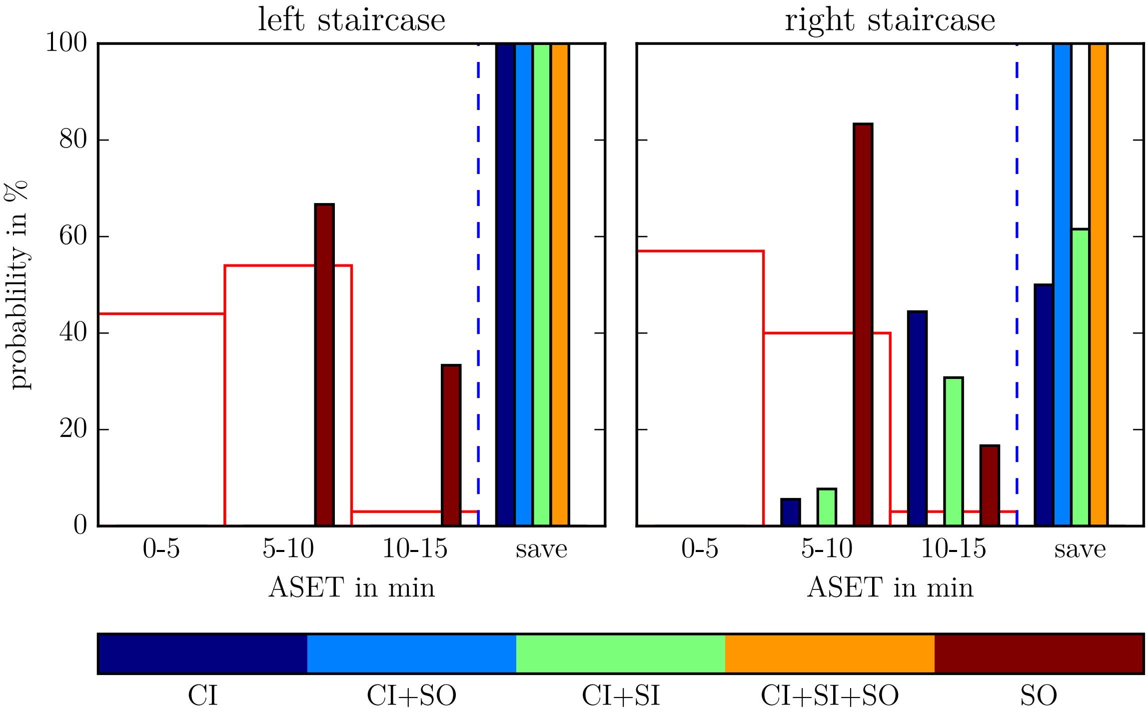

Figure 4: Probablility of a extraction strategy to achieve a ASET range for each staircases. The red bars in the background indicate the according probabilities for an unventilated case, which never satisfies a save condition. Color figures available in online version.

CONCLUSIONS

The consideration of not a single or just a few scenarios but a large ensemble provides a more robust insight into the performance of a smoke extraction system. The presented techniques aim to demonstrate the benefits of a comprehensive system analysis.

The assessment of the presented extraction systems shows that some systems can provide a higher performance with the addition of a localised additional system, here the performance of the ceiling inlet was remarkably increased by the addition of the staircase outlet.

As the system was slightly asymmetric, the results were not expected to be symmetric. However, the small asymmetry led to a notable difference in the results. It underlines that a systematic system analysis is crucial to enable resilient assessments.

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