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Article

Dispersion scenarios for pollution release in an occupied underground station – a numerical study with a micro-scale and a multi-agent model

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Abstract

The release of hazardous material in a subway station is a dangerous situation for passengers and staff. To achieve an acceptable level of risk, a correct marking of emergency exits and escape routes is essential., For this purpose, underground air dispersion, which depends on source characteristics, the construction layout of the station, and meteorological conditions, must be known. In this paper a micro-scale wind model is combined with a dispersion model to calculate the spread of pollutants underground as well as aboveground for specific scenarios. In particular, the effect of emission temperature on the contamination of the subway facilities was studied. Completely different spots with high concentrations have been calculated for hot and cold sources. Depending on the scenario, an escape route is not always safe, underlining the need for a situation-related adaptive marking system. Further information on the optimisation of a safe way out is provided by the results of an agent-based simulation model. Depending on the number and on the individual characteristics of the agents, the contamination level can be estimated, which could help in the prioritisation process between alternative escape routes.

Keywords: Micro-scale simulation, agent-based model, dispersion, subway

1 Introduction

Subway systems in larger cities play an important role in people's mobility and urban traffic planning. Since the opening of the first underground railway in London in 1863, millions of passengers have come to use this mode of transportation in more than 60 cities every day (Pan et al., 2013). Such a high concentration of people in the very narrow spaces of these underground facilities makes this system extremely vulnerable to faults, malfunctions and disasters, whether they are large or small. Unexpected events may have technical (e.g. power failure), accidental, or intentional causes. Out of this wide spectrum, fire has been recognised as the most dangerous element for passengers in subway systems (Gao et al., 2012; Fan et al., 2013; Hu et al., 2014).

Aside from small fires caused by short circuits, smouldering fires or by cigarettes burning in trash bins, catastrophic fires with the large loss of human life and property are also part of the long history of subway transportation. A fire at King's Cross station of the London metro system in 1987 resulted in the deaths of 31 people and more than 60 people being seriously injured (Fennell, 1988). During other severe subway fire in Daegu (Korea), nearly 200 people were killed in 2003 and in Baku (Azerbaijan) 289 people died during the 1995 metro fire. In Germany, 14 fire events with injured passengers have been reported since 1980 (Franz, 2014). The most serious incident was a fire in a metro car in Berlin in the year 2000, where roughly 350 people were rescued by the operating staff through a tunnel into the next station. Besides such severe accidents, subway systems are also potential targets for bomb and chemical or biological weapon terrorist attacks (Pflitsch et al., 2013).

To guarantee the smooth and safe operation of the underground network, the effects of such heavy disturbances must be studied in order to improve alarm systems, emergency exits, and to practice the cooperation of rescue units. Safety is the most important aspect when designing a subway system and evacuation routes must be sufficiently available, appropriate in size, and well signposted (Masuda and Arai, 2005).

In a disaster scenario, it is extremely difficult to predict the behaviour of a crowd of people who are experiencing fear and panic in a dim and narrow subway environment. For this reason, interdisciplinary research is necessary (BMBF, 2012) to identify the typical behaviour patterns of a crowd under various extreme disaster scenarios.

The instantaneous release of dangerous air pollutants is common to all the hazards mentioned above, be it fire or terror attack. This material is distributed in the subway facilities by their complex underground wind system and may contaminate the passengers (Pflitsch et al., 2013). The smoke of a fire is visible and people

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instinctively react by trying to escape quickly, usually in the opposite direction of the smoke and by following other persons without confirming whether this is safe or not. Invisible and odourless toxic gases are more dangerous because neither passengers nor rescue workers can recognise or identify them.

To protect passengers from potential toxic loads, a certain amount of information must be available within a very short time in order to initiate suitable countermeasures. Knowledge of the complex underground air flow of a system is the most important factor in estimating the diffusion path. In addition to extensive field measurements (e.g. Pflitsch, 2001; Straaten, 2015), a large number of highly sophisticated CFD models are available to simulate wind distribution, even with operating trains (e.g. Jia et al., 2009; Yan et al., 2013; Gross 2014b; Camelli et al., 2014).

Airborne material released inside the subway facility is transported by this underground wind and distributed within the metro station and tunnel system. Field experiments for well-defined scenarios have been performed (Kurioka et al., 2003, Hu et al., 2007; Potje-Kamloth and Welzel, 2011) which demonstrate the complex tracer gas dispersion. While the filling of a station by buoyancy-driven fire smoke is understandable, even neutral gases find their way through vertical connections to higher and lower levels (Spiegel et al., 2014). The results of such field measurements are used to validate CFD models, which are widely applied to predict the properties of air pollutants in tunnels and subway facilities (Flassak and Bächlin, 2012; Gao et al., 2012; Hu et al., 2014).

Detailed knowledge of airborne contamination serves as the basis for optimised rescue and evacuation measures for staff and passengers. In order to estimate the possible movement of a crowd under extreme conditions, agent-based simulation models can be applied (Masuda and Arai, 2005; Olfati-Saber, 2006; Yao et al., 2013; Brüne et al., 2014). For various scenarios, the bandwidth of the collective behaviour of a large number of interacting individual passengers can be studied in order to improve and adjust emergency plans and to eliminate weaknesses in the system.

In this paper, a micro-scale wind model is used together with a Lagrangian dispersion approach to simulate the spread of accidentally released air pollutants in a subway station. The release temperature has been varied in order to study the concentration distribution of a buoyancy-driven hot source, a gravity-dominated cold source, and a "neutral" source. The contamination of a crowd of escaping agents is specified in number and intensity by the application of an agent-based simulation model.

2 The model system

2.1 The wind model

A micro-scale model, ASMUS (**A**usbreitungs- und **S**trömungs**M**odell für **U**rbane **S**trukturen), is used to calculate wind and temperature distribution in the area of interest in the atmosphere as well as in the subway system. The model has been verified against various wind tunnel measurements according to VDI 3783 and has been applied to various studies in a built-up environment (Gross, 2012, 2014a).

The model is based on the Navier–Stokes equations with anelastic approximation, and the continuity equation and the first law of thermodynamics are used to calculate the mean wind $\bar{u}_i$ and temperature. These equations are Reynolds averaged and the resulting correlations of fluctuating quantities are parameterised by flux–gradient relationships. The eddy exchange coefficient, K, introduced by this approach is determined using the Prandtl–Kolmogorov relation via turbulence kinetic energy, E, which is calculated with an additional prognostic equation. However it should be noted, that this pragmatic approach, widely used successfully for calculating atmospheric conditions, may lead to uncertainties near the obstacles. As shown by Griebel et al., (1995), the turbulent flow regime breaks down very close to the walls and the turbulence model used here approaches its limits.

Obstacles are introduced into the model by a porosity concept (Gross, 2014a), where buildings and walls are represented by impermeable grid volumes with porosity $P = 0$, while $P = 1$ is used else.

The set of model equations is solved on a numerically staggered grid, where all scalar quantities are arranged in the centre of the grid volume, while velocity components are defined at the corresponding side walls of the grid. The pressure disturbance is calculated by solving a three-dimensional discrete Poisson equation directly with Gaussian elimination in the vertical and fast Fourier transforms in the horizontal directions. A grid resolution of $\Delta x = \Delta y = 1$ m is used in horizontal directions and in the vertical directions $\Delta z = 0.5$ m is adopted. The model equations are integrated forward in time with a time step, Δt, satisfying the CFL criterion.

The boundary conditions for the velocity components in all indoor building surfaces are zero (no-slip conditions) and turbulence kinetic energy is proportional to the local friction velocity squared. The friction velocity is calculated assuming a logarithmic wind profile between the surface and the closest grid value in the atmosphere, with stability functions according to Dyer (1974). This approach is used here although the logarithmic wind profile becomes questionable very close to the wall in the transition layer of the turbulent and the laminar flow regime. At the open lateral boundaries with $P = 1$, no-flux conditions for all variables are used.

A first application of the model for a subway system, including more model details, are given in Gross (2014b).

2.2 The dispersion model

A Monte Carlo model was chosen to calculate the transport and diffusion of a chemical non-reactive pollutant.

The locations of individual particles for time $t + \Delta t$ are determined by:

$$x_i(t + \Delta t) = x_i(t) + U_i(t)\Delta t \qquad (2.1)$$

where x_i are the coordinates of the i-th particle, U_i is the particle velocity, and Δt is the time step.

The particle velocity, U_i, is partitioned into mean velocity, $\bar{u}_i$, simulated by ASMUS, and a turbulent component, u'_i. The latter is calculated as:

$$u'_i(t + \Delta t) = R_{Li}(\Delta t)u'_i(t) + \sqrt{(1 - R_{Li}(\Delta t)^2)}\sigma_{u'_i}\Psi \qquad (2.2)$$

which describes a Markov process of first order. The Lagrangian autocorrelations are as follows:

$$R_{Li}(\Delta t) = \exp(-\Delta t/T_{Li}) \qquad (2.3)$$

where T_{Li} is the Lagrangian time scale for the velocity, u'_i, and Ψ is a random number from a Gaussian distribution with a mean of zero and a standard deviation of $\sqrt{(1 - R_{Li}(\Delta t)^2)}$. The mean velocity, $\bar{u}_i$, and the turbulence kinetic energy, E, are available from ASMUS. For this purpose, the following relation between E and $\sigma_{u'_i}$ is used (Gross et al., 1987):

$$\sigma_{u'_i} = \sqrt{2m_iE} \qquad (2.4)$$

with $m_i = (0.54, 0.30, 0.16)$. The Lagrangian time scale for each component, T_{Li}, is determined by the combination of the Taylor theorem with the variance relationship for Fickian diffusion:

$$T_{Li} = K(\sigma_{u'_i})^{-2} \qquad (2.5)$$

For the simulations presented here a release of 100 particles per second, representing a source emission rate of 100 units/s, was adopted.

2.3 The multi-agent model

A simple agent-based simulation model was used to study the evacuation of a subway station and the contamination for various emission scenarios. The movement of the agents are calculated in increasing order of numbering. However, the first agent, where the calculation sequence starts, is always randomly selected. An agent in our context is an autonomous entity with pre-defined properties and possible actions. The general conditions for the agents and the rules for interactions are as follows:

- each agent has an individual walking speed, U_a;
- in tunnels, on stairs, and for increased crowd density U_a is reduced;
- the agent tries to proceed to pre-defined targets (e.g. exits) fast and by the shortest route;
- the agent avoids collisions with nearby obstacles and other agents.

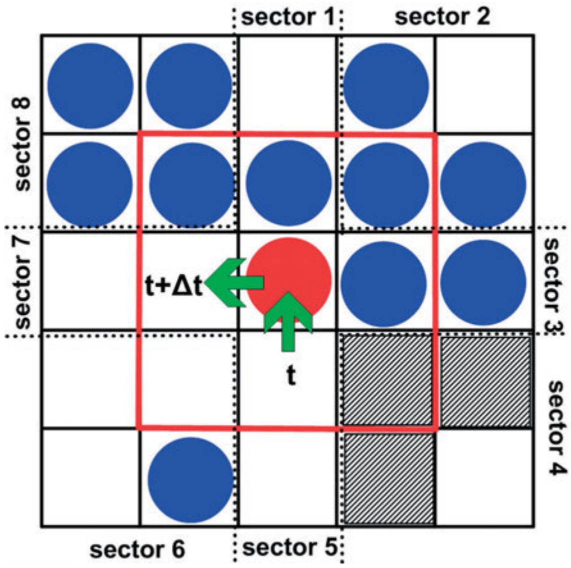

Figure 1: Sketch to demonstrate the decision-finding for the next step ($t + \Delta t$) of farther movement of an agent (red dot) depending on the number of other agents (blue dot) or obstacles (hatched).

These rules are included in the model framework by calculating the number of neighbours in the adjacent grid cells and the subway building characteristics, such as walls, stairs, or tunnels in the agent's way. However, in the simple model presented here, the agents are considering on their paths only the direct surrounding (like a scenario with limited visibility) and not the foresight of the overall situation. In the case of obstacles or other agents in the direct path of the target, the individual agent tries to go around them and find an alternative route. The agent's highest priority is to move more or less in the direction of the target, whereas their lowest priority is moving in the opposite direction. If the direct route is blocked, the agent tests other possibilities. The order of the attempts depends on the number of obstacles in the direct two-grid surrounding considering the priority mentioned before. An example for such a decision is given in Fig. 1. A further movement of the agent towards the target, which is in the direction of sector 1, is blocked by another agent. The next step ($t + \Delta t$) is into sector 7, because sector 2 as well as sector 8, which are closer to the direction of the target, are more occupied.

Following Masuda and Arai (2005), the agent's walking speed is empirically reduced depending on the local situation (Table 1). However, in any case it is not allowed for the agent to occupy an area (= grid cell) which is not free. In this case walking speed is further reduced to match the velocity of the nearby agents or even come to a standstill.

In Fig. 2 two examples are given to demonstrate the obstacle avoidance capability and the walking speed adaption of the simple agent model. The paths of 10 agents out of 300 randomly distributed in the starting zone (SZ) are shown. The task is to find the shortest way from SZ to the final target (FT) by passing an intermediate target. All agents have the capability to walk with

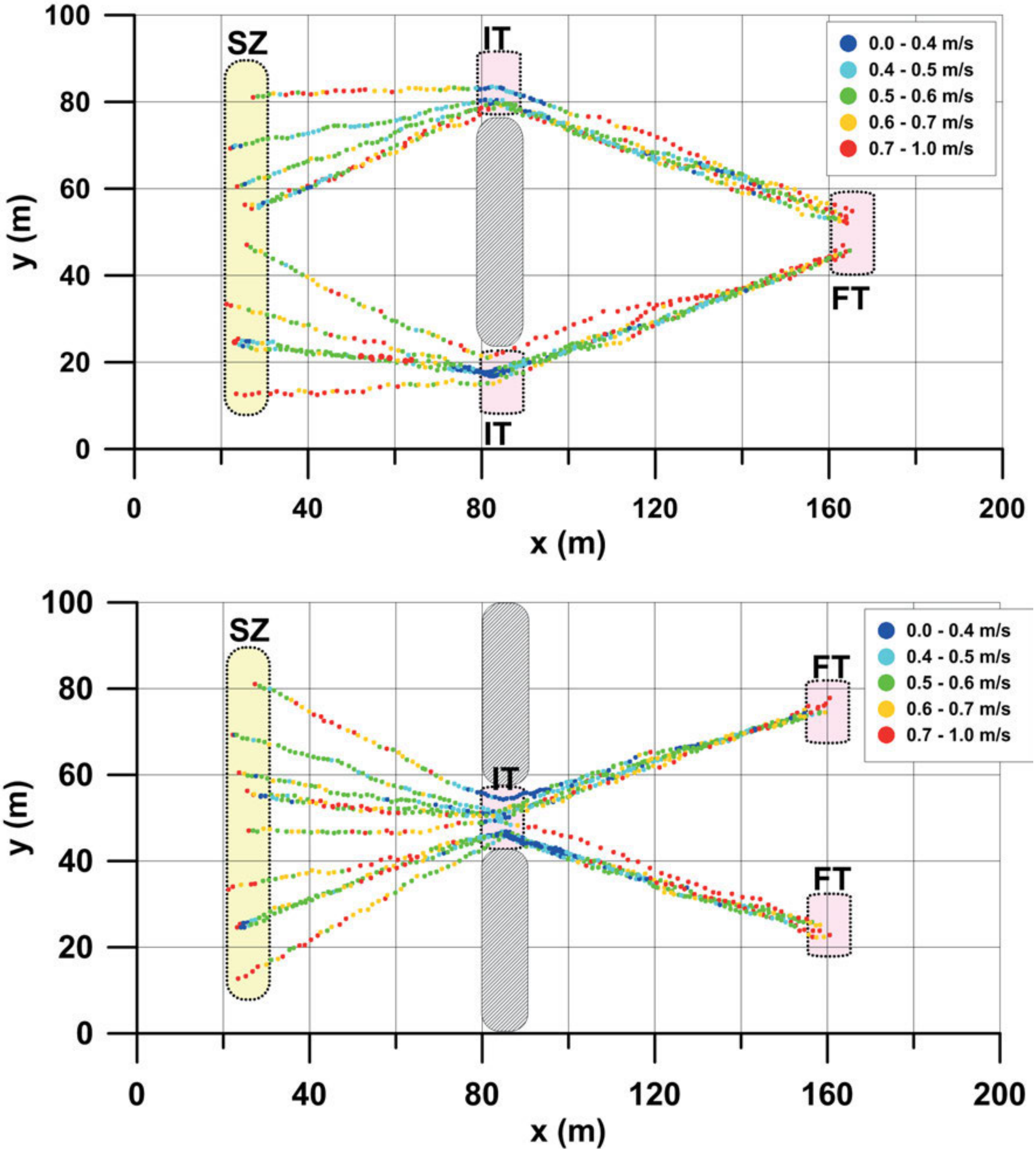

Figure 2: Path and walking speed of selected agents for walking around an obstacle (above) or through a passage (below).

a speed of 1 m/s. However, due to overcrowding and gathering in the starting zone and in the area of the intermediate targets (IT) walking speed is typically much slower. Only some agents that find a free path at the lateral edge of the crowd reach full speed and get to the final target much earlier.

Table 1: Reduction factor of walking speed depending on the number of obstacles or agents in the direct surroundings (red line in Fig. 1).

obstacles/agents	walking speed factor
1–2	1.0
3–4	0.75
5–6	0.5
7–8	0.25
On stairs	0.5
in tunnel	0.5

2.4 Input parameter

The simple geometry of Königsworther Platz subway station in the Hannover subway system is adopted for this study. With a horizontal grid resolution of 1 m and a vertical grid resolution of 0.5 m, not all of the details of this station can be considered in the numerical simulation. However, the characteristic features of this underground facility are well represented. Vertical and horizontal cross sections of the model station are given in Fig. 3.

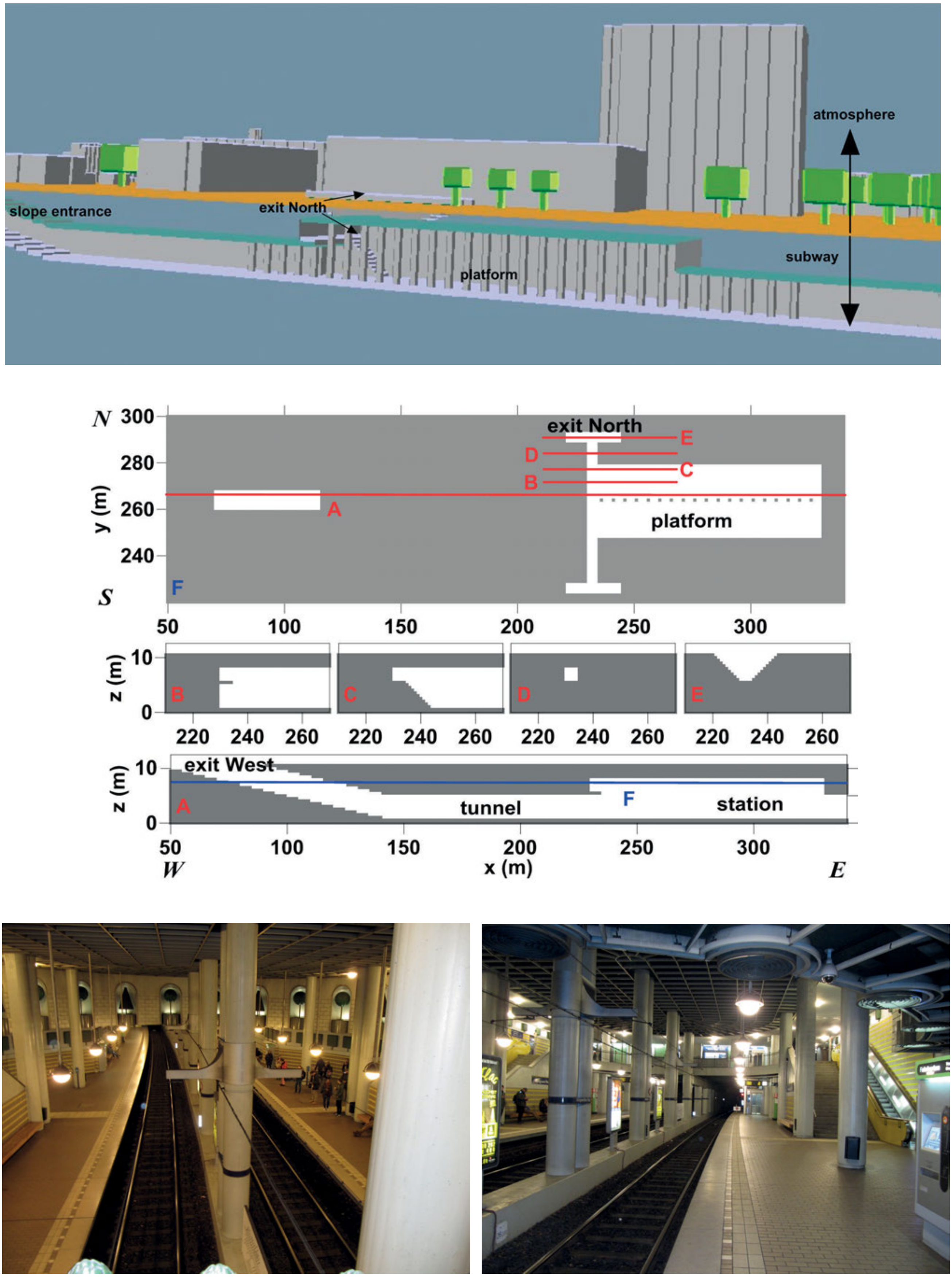

Figure 3: Grid representation of the Königsworther Platz subway station in a perspective view (above) and in horizontal and vertical cross sections (middle). Only the central part of the simulation area is shown. Pictures of the real station are given below.

The main body of the station consists of a 100-m-long hall (Fig. 3) with stairs and elevators at one end to reach the upper levels. Two tracks are located in the central part with two side platforms, one for the trains going in either direction. The station ends on both sides in tunnel openings. The tracks lie 1 m deeper than the platforms in the station to allow passengers easy access. As a structural requirement, the two tracks are separated by a row of columns. A special feature of this station is the climb of the tunnel and that after the west exit (A) the trains run above ground.

Stairways and escalators allow passengers to proceed towards the upper level (C), where narrow passages (D) lead to the exits. Following the stairways (E), passengers will reach street level within a complex building environment.

It should be mentioned here, that by considering only a single station the linkage to other stations and the tunnel system with multiple interactions to the air flow are not included in this study.

Since the above-ground situation is important for the subway air flow but is not in the focus of this study, the building and tree distribution is not described here in detail. An impression is given later in Fig. 7. However, the buildings are still of relevance to the underground situation because the air flow in the lowest boundary layer at the exits determines, to a certain extent, the wind distribution and ventilation of the station.

The vertical resolution of the numerical grid in the atmosphere is 1 m from the ground up to 20 m with an expanded grid above. With the grid resolution used here, the area around the Königsworther Platz subway station is represented in the model by 700×500×65 grid points.

The meteorological conditions adopted here are associated with a moderate air flow from westerly directions. As described in Gross (2014b), a pressure gradient in the subway system must be specified in order to maintain the persistent underground motion throughout the simulation period. For the simulations presented here, a subway wind of approximately 0.5 m/s and a near-surface wind in the atmosphere of 2 m/s are used. The temperature distribution in the subway facilities was adopted according to observations (Straaten, 2015) with $T = 17\,°\mathrm{C}$ inside the tunnel and the station and $T = 7\,°\mathrm{C}$ at street level.

Train movement was not considered in this study as it is very likely that the train service has been shut down completely in an emergency situation.

3 Results

3.1 Dispersion in the subway station

The emission of airborne material in a subway station can occur at very different locations (e.g. Gao et al., 2012) in very different ways. In this paper we study the effect of specific release temperatures on the dispersion of airborne material in a subway system. In the "hot source" scenario, the release of material is associated with a temperature increase at the source by an additional 50 °C. This is the order of magnitude found in experimental data and used in other numerical studies (Fan et al., 2013; Gao et al., 2012). In the "cold source" scenario, the source temperature is decreased by 20 °C compared with the surroundings, while for the "neutral" scenario the emission is not coupled with a temperature change.

The total time period covered by a simulation is 15 minutes. In the first 5 minutes the subway wind system adjusts to the superimposed conditions, followed by the instantaneous start of the emission. A continuous source was assumed for the next 10 minutes, where the temperature at the release point was adopted according to the scenarios mentioned above.

Simulated wind and concentration patterns are presented in Fig. 4 in vertical cross sections of position A (see Fig. 3). For the "neutral" scenario the atmospheric wind at street level enters the tunnel system resulting in a westerly flow of approximately 1 m/s into the station and an outflow into the eastern tunnel of 0.5 m/s with minor changes due to the widening of the station. The airborne material, released near the ground at $x = 270$ m, is captured by the flow and transported through the subway system. On the windward side of the source, only low concentrations are calculated because fresh and unpolluted air is advected out of the tunnel. Some particles, representing the dispersion of air pollutants, find their way to the windward side of the source, but only due to a light return flow in the upper section of the station. The main part of the released material is transported with the background flow in easterly directions and enters the tunnel in higher concentrations

A very different picture is simulated for the "hot source". The very warm air, which is 50 °C warmer than the surroundings, rises in a narrow plume with high vertical velocities up to 5 m/s. A strong divergent horizontal wind in the upper part of the station distributes the pollutants throughout the subway facility. In the eastern tunnel as well as in the gallery at $x = 230$ m, which enters into the north exit, high concentrations can be found. It is only the unpolluted air coming out of the western tunnel that reduces the concentrations in this part of the station.

The colder and heavier air in the third scenario moves like a gravity current along the platform in all directions with wind speeds of 2 m/s. The current moving to the west is in opposition to the background air flow out of the tunnel, causing the warmer air in its way to rise. In this way a concentration load throughout nearly the entire station can be found. However, on the eastern side of the source, a moving gravity current and background air flow are advecting high concentrations into the tunnel in the same direction.

The asymmetry of the background wind speed in the inflow tunnel and the exit tunnel is reason enough to initiate a series of simulations. For the "hot source" scenario, the effects of the type of tunnel entrance, either a sloped tunnel or a flat tunnel, were studied. Temperature

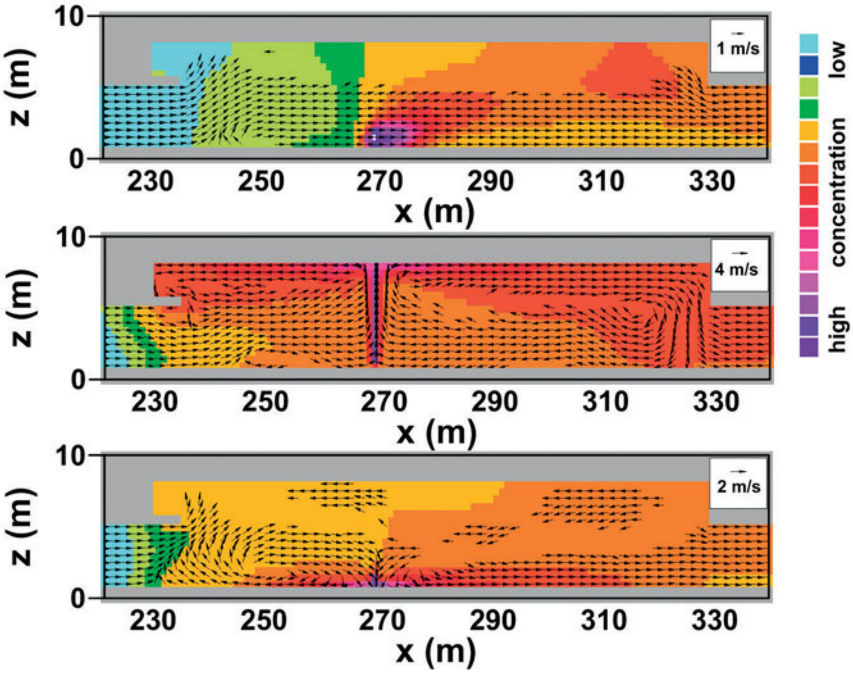

Figure 4: Vertical cross sections (y = 266 m) of wind and concentration for a "neutral source" (above), a "hot source" (middle) and a "cold source" (below). Vectors have different scales (see text).

and wind distribution in a vertical cross section along position A underline the significant differences (Fig. 5). While the temperature inside the tunnel is constant for the flat tunnel scenario, a large temperature gradient is evident for the sloped tunnel scenario. Cold air from outside is transported into the tunnel system via the superimposed wind above ground from the west and by gravity, causing an additional horizontal pressure gradient and an acceleration of the tunnel air.

In a horizontal cross section at a height of z = 8 m, which is below the ceiling but which also covers the passage to the north exit, the effects of the sloped entrance on the air exchange between the station and the outside ambient air is evident (Fig. 5). The rising warm plume properties are distributed in the lateral directions. The much stronger inflow in the sloped tunnel scenario is embedded in this circulation system and causes significant air ventilation through the north and south exits. On the other hand, the weaker inflow in the flat tunnel scenario is not sufficient to cause effective ventilation. It is only through the north exit, which is closer to the hot source, that the relevant transport of polluted air to street level is simulated, while simultaneously an inflow of cold air from street level is calculated through the south exit.

Vertical profiles of the outflow of the tunnel into the station show that the tunnel's architecture is responsible for the stronger penetration of the outer air flow into the station (Fig. 6). The additional heat source only modifies the overall tunnel flow. The wind profile for the flat tunnel shows a parabolic curvature, while in the sloped tunnel scenario a pronounced maximum in the lower part is simulated. The maximum is more than double the value for the sloped tunnel scenario compared with the flat tunnel. Similar flow characteristics have been observed during field experiments in the Hannover subway system (Straaten, 2015). During 6 full nights, wind and temperature have been observed by a team of up to 19 people with three fixed ultrasonics and numerous mobile measuring systems. These night time observations without running trains in different tunnels leading into various stations show a similar behaviour as calculated. Wind speed is much higher at the tunnel entrance into the station when the distance to street level is short as opposed to when a station is fully incorporated in the subway system. Measurements in three consecutive stations show that it is only in the station located nearest to the above-ground exit that wind speed is significantly higher than in the two following stations, where the background flow with a reduced wind speed is fully established.

An s-shaped outflow profile, simulated in the passage to the north exit for the scenario without a source inside the station, was also found in the observations. The near-bottom penetration of cold air from street level causes the inflow in the lower part of the profile, while the distinct flow regime in the passage is completed by the outflow of the subway system's warmer air below the ceiling. The outflow is enhanced with the additional effect of a hot source in the station. A typical observed s-shaped profile, which shows the same characteristics, is also given in Fig. 6. However, the cold-air inflow from outside is stronger due to the different station architecture and a stronger temperature difference during the observations. For the sloped tunnel scenario, the stronger inflow into the station from outside causes very efficient ventilation through the passages with high wind speeds.

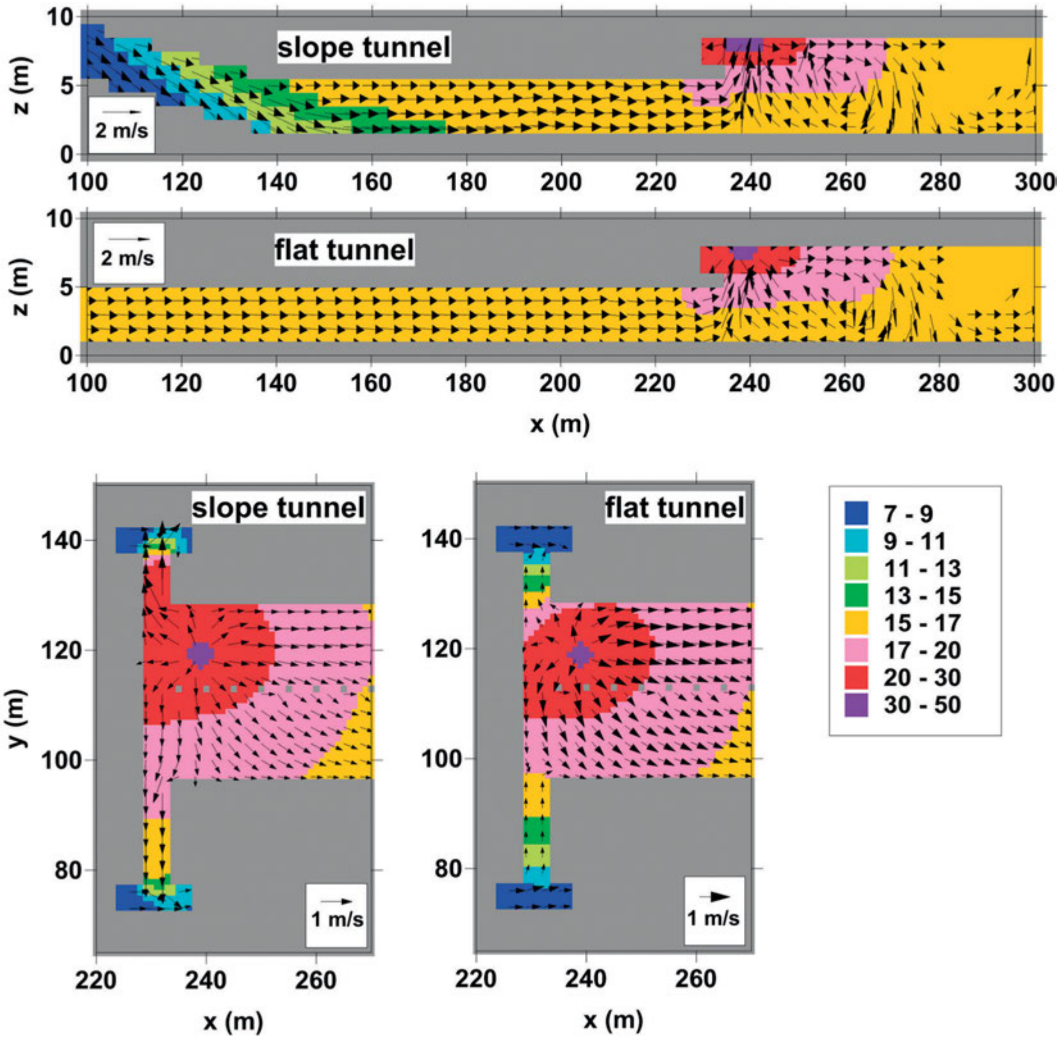

Figure 5: Above: Vertical cross sections ($y = 266$ m) of wind and temperature (in °C) for the "hot source" scenario for a sloped tunnel with an exit to street level and a flat tunnel. Below: horizontal cross sections ($z = 8$ m) of wind and temperature for the "hot source" scenario for a sloped tunnel and a flat tunnel.

This strong outflow, intensified by the escape of much warmer air for the "hot source" scenario, prevents the penetration of cold air from outside.

The underground and above-ground atmosphere are strongly coupled by the air mass exchange through the exits. Depending on wind direction, winds above ground can enter into the subway system through tunnel exits or entrance facilities such as passages or stairs and modify the persistent underground background air flow. The temperature difference between the air inside the subway and the atmosphere, which might be significantly large (Pflitsch et al., 2013), is also a dominant factor that controls the underground wind, either through near-surface penetration of cold air or through reduced or enhanced turbulent mixing depending on thermal stratification.

For the subway facility considered here with a west–east running tunnel, only a superimposed wind coming from a sector in the southwest to the northwest is channelled at the exit, causing higher wind speeds inside the tube. Changing the wind direction to a cross-flow, a vortex is formed in the lowered exit region with only a weak inflow. Finally, an oncoming wind at street level from east does not enter the tunnel exit at Königsworther Platz. This overall picture is only valid for a small temperature difference between station and street level. For a night-time or winter scenario with cold air outside, the air mass will always infiltrate into the tunnel due to gravity. However, it should be noted that for a stronger natural underground wind from the east it is not an inflow due to gravity, but an outflow caused by the larger scale pressure gradient that will characterise the wind pattern at the tunnel exit

The air pollutants released at a source close to the platform are distributed in different ways in the station depending on the wind field and turbulent mixing. Due to the limited path of diffusion, concentrations, in general, are high with local extremes (Flassak and Bächlin, 2012). The simulated strong outflow through the passage to the north exit transports polluted air into the street-level atmosphere. These pollutants are very effectively distributed in the building environment above

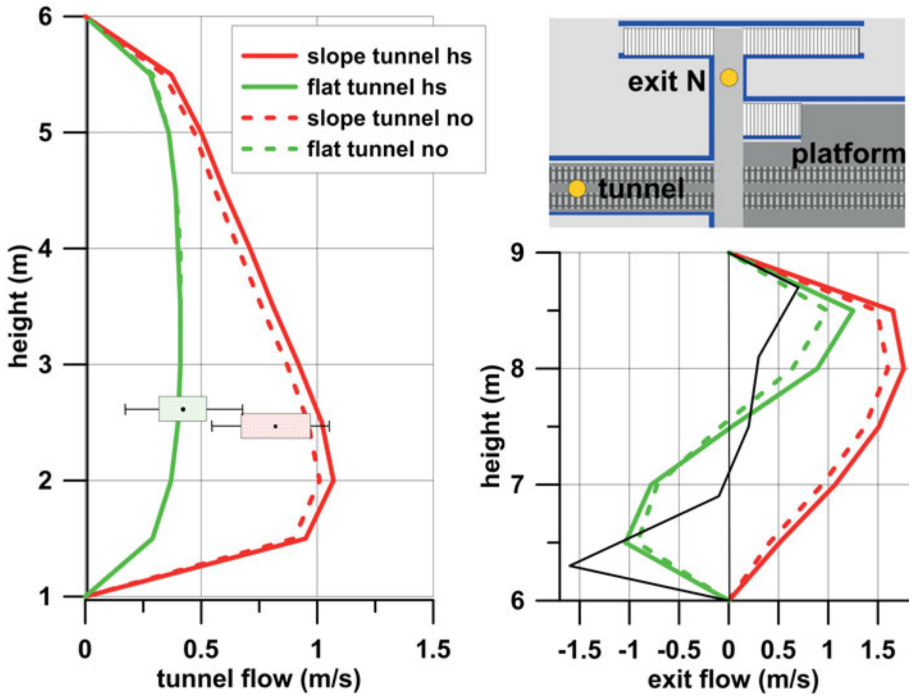

Figure 6: Left: Vertical profiles of tunnel flow for a sloped and a flat tunnel, with (hs) and without (no) a "hot source". Observations of Straaten (2015) are included (Box-Whiskers). Right: Vertical profiles of exit flow for a sloped and a flat tunnel, with (hs) and without (no) a "hot source". Observations of Straaten (black line) are included.

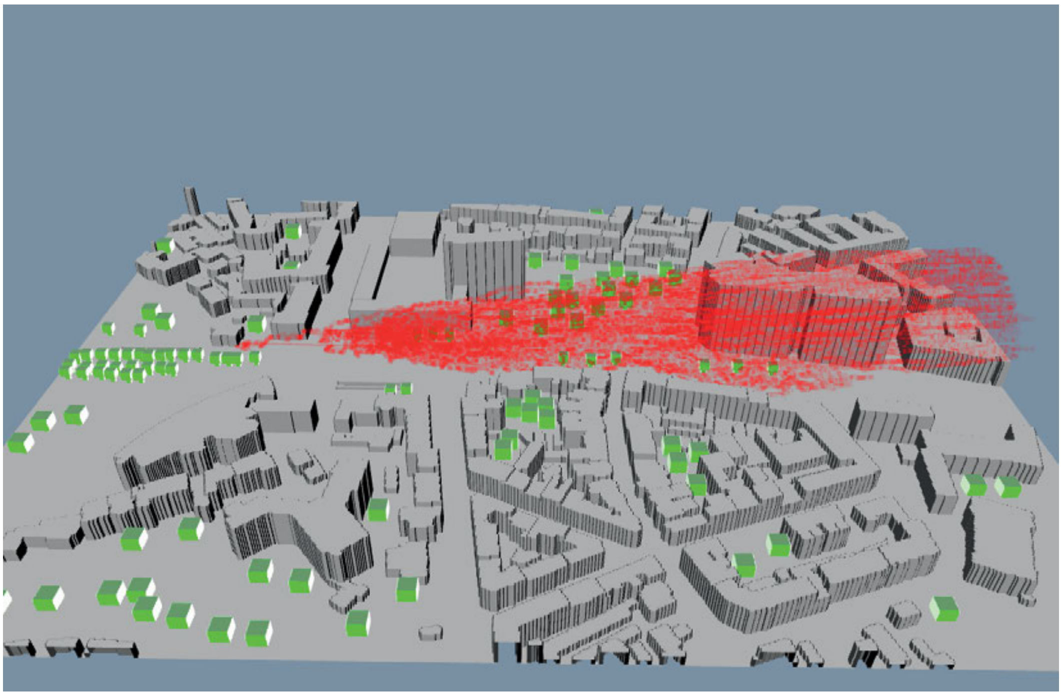

Figure 7: Above-ground distribution of particles (red) which escape through the north exit into the building environment for a superimposed wind from the west. Trees are indicated in green.

ground because a large volume of the atmosphere is included into the diffusion process and the higher wind speeds ensure a fast and effective transport into the surroundings. Consequently, an urban district is also affected by an underground source, which underlines the necessity of always looking at the complete system. As an example, the atmospheric dispersion of pollutants for the "hot source" scenario which escape through the north exit are given in Fig. 7 together with the complex building and tree configuration used in the simulations. However, the above-ground situation is not the focus of this study and will not be discussed in further detail.

3.2 Multi-agent simulation

Shortly after the release of air pollutants in the three scenarios, the subway facilities are contaminated in very different ways. While for the "neutral" source only the eastern part of the station is affected, the strong chimney effect for the "hot source" scenario transports the pollutants upwards along the stairs and the passage and contaminates the most logical evacuation route to outside. For the "cold source" scenario the emitted pollutants are initially spread out horizontally and remain there in higher concentrations due to gravity on the platform. However, it is not only the station that is affected by the emissions, but also the eastern tunnel. The natural background flow as well as the source-induced secondary circulation transport airborne material into the tunnel tube.

These complex contamination patterns of the subway facilities make it extremely difficult to distinguish between safe and unsafe evacuation routes. To demonstrate some difficulties, a number of evacuation scenarios are studied with an agent-based simulation model. A number of agents with pre-defined properties and possible actions are located along the platform and are alarmed and prompted to leave the station 2 minutes after the release of the pollutants. This is a typical reaction time (awareness time + response time) after being alarmed (Pribyl and Pribyl, 2014; Brüne et al., 2014). After this alarm, the agents walk in time steps of 0.33 s with their individual speed, depending on age, fitness, crowd density, and location in the station to their next destination. On their individual paths the agents walk through the polluted station and inhale the unhealthy air. By calculating the total dosage along the route from the platform to the exit above ground, it is possible to compare the risk level to the agent's health for different evacuation routes. While the individual position of an agent can be somewhere inside a grid cell, the concentration of the grid point is always used for calculating the dosage.

In the first study a different number of agents are alarmed. The starting positions are randomly chosen on the platform and all agents are physically able to walk at the same speed. All agents follow the same route from the platform to the stairs and further through the passage and the stairs to the final exit above ground. If only a few people are on site, the maximum evacuation time is about 140 s (Fig. 8), which is also the theoretical time for an agent to walk at maximum speed from the farthest edge of the station to the exit. As some agents are much closer to the stairs, the mean evacuation time for all the agents is only about 110 s. As the number of agents increases it takes more than double the maximum time for 400 people to clear the station completely.

On their way to outside agents walk in a contaminated atmosphere, the impact of which on the agents' health differs in the three emission scenarios. Dispersion calculations have been performed with a normalised source. In order to get a more illustrative measure, the dosage, D, for each agent, starting at the platform

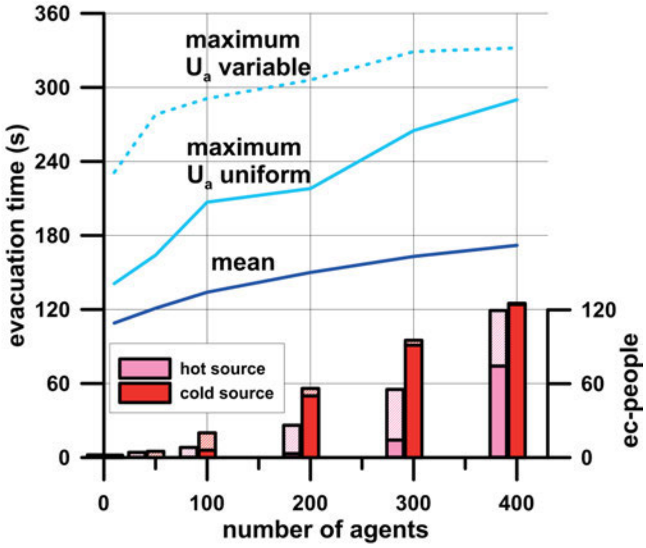

Figure 8: Relation between evacuation time and number of agents and number of extremely contaminated (ec) people for different emission scenarios. Light pink rectangles are the additional ec-people if fast and slow agents are allowed.

and ending at the final safe environment outside, has been calculated as integrated concentration along the individual paths of the moving agents. The resulting dosage was interpreted in terms of health risk as harmless ($D < 1000$ units), followed by low, medium, and high in increments of thousands, and finally extreme for $D > 4000$ units. This evaluation serves only to communicate the wide range of escape routes with a very different health risk.

The numbers of extremely contaminated people for the "hot source" and "cold source" scenarios are given in Fig. 8. For the "neutral" source all agents find a relatively safe way out, even those starting at the farthest edge of the station. It is only in the eastern part of the station that they walk within high pollution concentrations (see Fig. 4) while passing the source, the air is much cleaner and the following increase of the individual dosage is small. The load of all agents is much smaller than the threshold for the extreme category. For the "hot source" scenario, parts of the evacuation route are highly contaminated. The polluted warm air finds a way outside, especially along the staircases and through the passage, and the evacuation route and polluted areas overlap almost completely. For a small number of agents, walking speed is high and the duration of the stay is short. However, if a larger number of agents escape from the platform after the warning, the stairway to the exit is too small to allow people to walk fast. Consequently, they stay much longer in the unhealthy air and individual dosage increases. For the scenario in which there are 300 agents, 5 % of them will be loaded with an extreme dosage. The "cold source" scenario has the worst outcome, as the cold and heavy pollutants disperse close to the platform within the fleeing crowd. In this case a large number of extremely contaminated people are simulated. The order of magnitude is 25–30 % for a number of agents larger than 200. Walking speed is the key factor in determining a safe evacuation. In order to study this effect of this parameter, 20 % of the agents are assumed to be young and very fit people and their mean U_a of 1 m/s was amplified by 50 %. On the other hand, elderly or handicapped people are not able to walk fast and for this group walking speed was reduced by 50 %. In this case the time to clear the station is much longer and is defined by the group of slow people. For a small number of agents the evacuation time is up to 70 % longer and for a larger number up to 30 %. As now more people stay for much longer inside the polluted station, the number of extremely contaminated people increases drastically.

In a more broadened simulation the number of permitted exits is enlarged as well as the composition of the group members. In addition to the evacuation route following the stairs upward and through the passage, the agents are also allowed to escape through both tunnels. Due to bad visibility and uncomfortable walking conditions, the speed of the agents is reduced inside the tunnel to half of the maximum value. Out of the total number of 400 agents, 50 % choose the route via stairs and passage on the first floor to the north exit, 25 % select the west tunnel, and 25 % select the east tunnel. The maximum walking speed was also adapted to the specific passenger spectrum described above. These both modifications, walking speed and exits, were randomly assigned to the agents.

As an example, the escape routes of three agents with different destinations are given in Fig. 9. The colour indicates the accumulated pollutants for the individual agents along their paths. If the dosage is above the extreme threshold, the agent stops and acts as an obstacle which must be avoided for the other agents. For the "neutral" scenario the rescue paths to the north exit and west tunnel are very safe, while the agent taking the east tunnel moves directly into the polluted air and their dosage increases to a medium value. The "hot source" scenario is characterised by an effective diffusion of the pollutants throughout the entire station with local extreme values. For this reason the agent moving into the west tunnel receives a higher dose of pollution than for the same destination in the "neutral" scenario. However, since they are moving towards the region with fresh air, the integrated exposure is low. A very different situation can be found for the agent heading into the east tunnel. The relatively high pollution concentration inside the tube together with a low walking speed are unfavourable conditions for a safe and healthy route. The fastest way to escape the station is to use the stairs to the upper level, through the passage and out through the north exit. However, for this emission scenario the air pollutants choose the same path and therefore the evacuation route is highly contaminated. The agent's dosage increases continuously on the way out and reaches a high level after arriving above ground. Finally, for the "cold source" scenario all escape routes start at the platform where the maximum concentrations occur. The contamination of the agents just after they have started moving is high and increases continuously as the agents make their way out. In this case, the west tunnel is the relatively safe evacuation route, while it is very dangerous to head to an exit through the east tunnel or the north exit.

Through a statistical analysis of the contamination of all of the 400 agents used in this study, it is possible to differentiate between relatively safe and unsafe exits. The distribution frequency of the percentage of people with different concentration loads is given in Fig. 10 and illustrates the large differences on the health effects of the agents for the evacuation routes adopted here. The north exit can be recommended as evacuation route for the "neutral" source, while a moderate number of agents are loaded with an extreme dosage for the "hot" and the "cold" source. The west exit tunnel is the preferable choice for all source types. The large number of people with extreme exposure can be identified as agents with a reduced walking speed. This group is less favoured in all circumstances. For the westerly background air flow in the station used here, the east tunnel cannot be recommended as a safe evacuation route.

It should be mentioned that the results and conclusions presented above are valid only for the specific set of input parameters.

4 Conclusions

In this paper, a micro-scale wind and dispersion model was combined with a multi-agent approach to study the evacuation of a subway station in the case of the release of airborne material., As the underground dispersion of an air pollutant is determined by a wide range of factors, the results presented here should be considered as a feasibility study for identifying the importance of specific parameters. It is absolutely essential to prepare emergency plans to guarantee the safety of metro passengers to the greatest extent possible. Aside from other approaches, physical and mathematical models can be adopted for a scenario-based analysis to evaluate different scenarios and their effects on safety. However, such model results should be verified against the findings of field experiments.

Although a numerical model is a universal tool for predicting subway dispersion, its routine applicability is strongly limited by the wide range of possible meteorological conditions and computing time. However, a possible solution to this dilemma is the calculation in advance for a number of scenarios which are then saved in a library for reuse. Such a promising concept will be checked and pursued in the Orgamir project together with more empirical approaches. It is well known that subway dispersion is strongly determined by underground air flow, which in turn is affected by the meteorological conditions above ground and modified by the construction layout of the metro facilities. As demonstrated in this paper, even the specific geometry of the

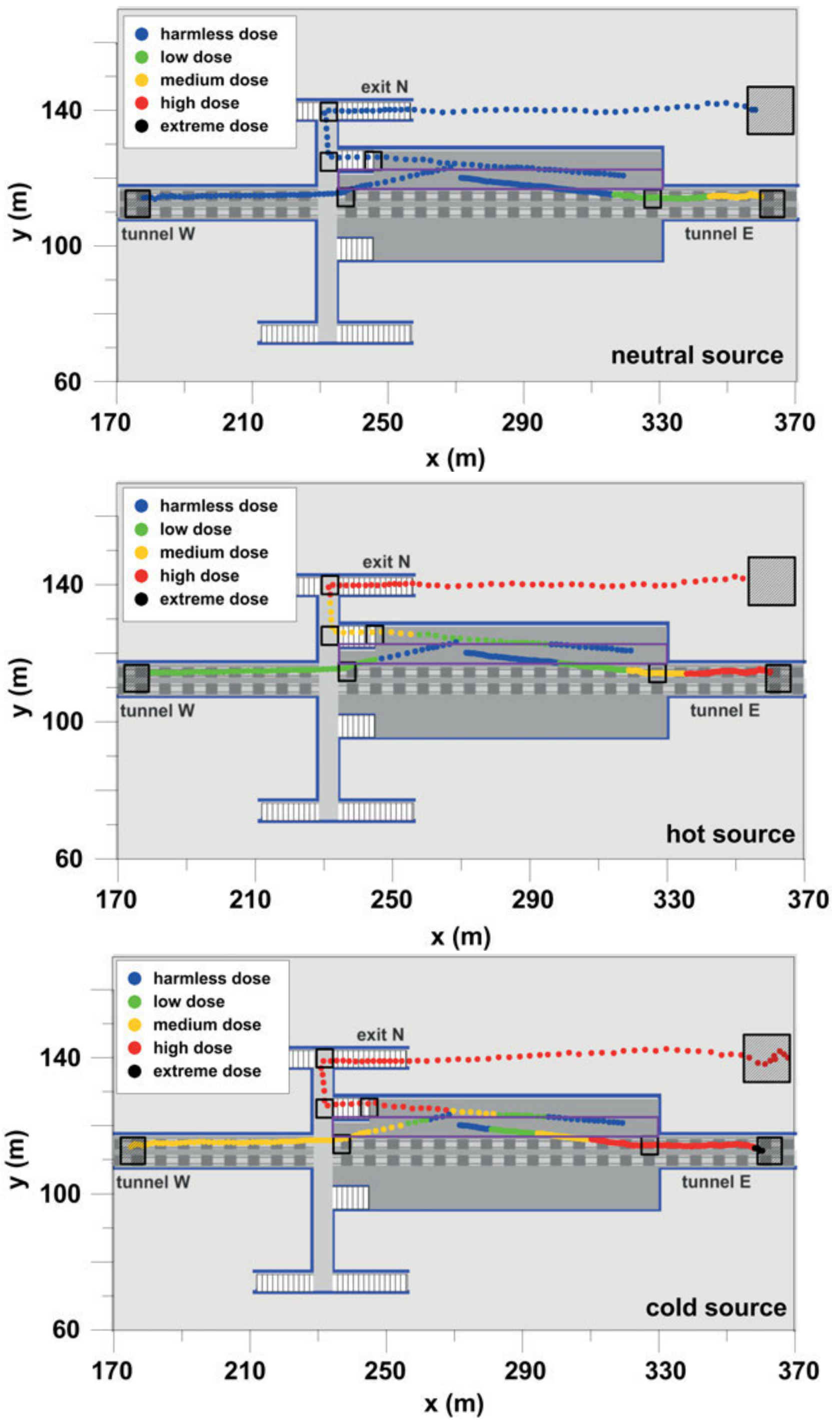

Figure 9: Rescue paths of the selected agents for the three source scenarios. Colour indicates the absorbed dosage. Open rectangles are intermediate targets and hatched rectangles the final targets for the agents.

tunnel entering a station modifies the wind pattern significantly. Due to the large number of parameter combinations, it seems to be unrealistic and disproportionate to simulate underground wind for all possible situations. Instead, the numerous numerical results should be used to cluster and identify characteristic wind patterns and to develop empirical estimates for each individual subway station.

A similar picture emerges when looking at the underground spread of an air pollutant. The knowledge of the exact source location within the very limited space for dispersion is essential for a realistic estimation of the local contamination inside a subway station. Another important factor in this context is the release temperature at the source. As shown in this paper, the diffusion paths of materials, emitted as “cold”, “hot”, or thermally “neutral”, vary completely and in each scenario different parts of the station are polluted to a certain degree. In the “hot source” scenario the warm air fills the hall very quickly and finds a way through openings to the upper

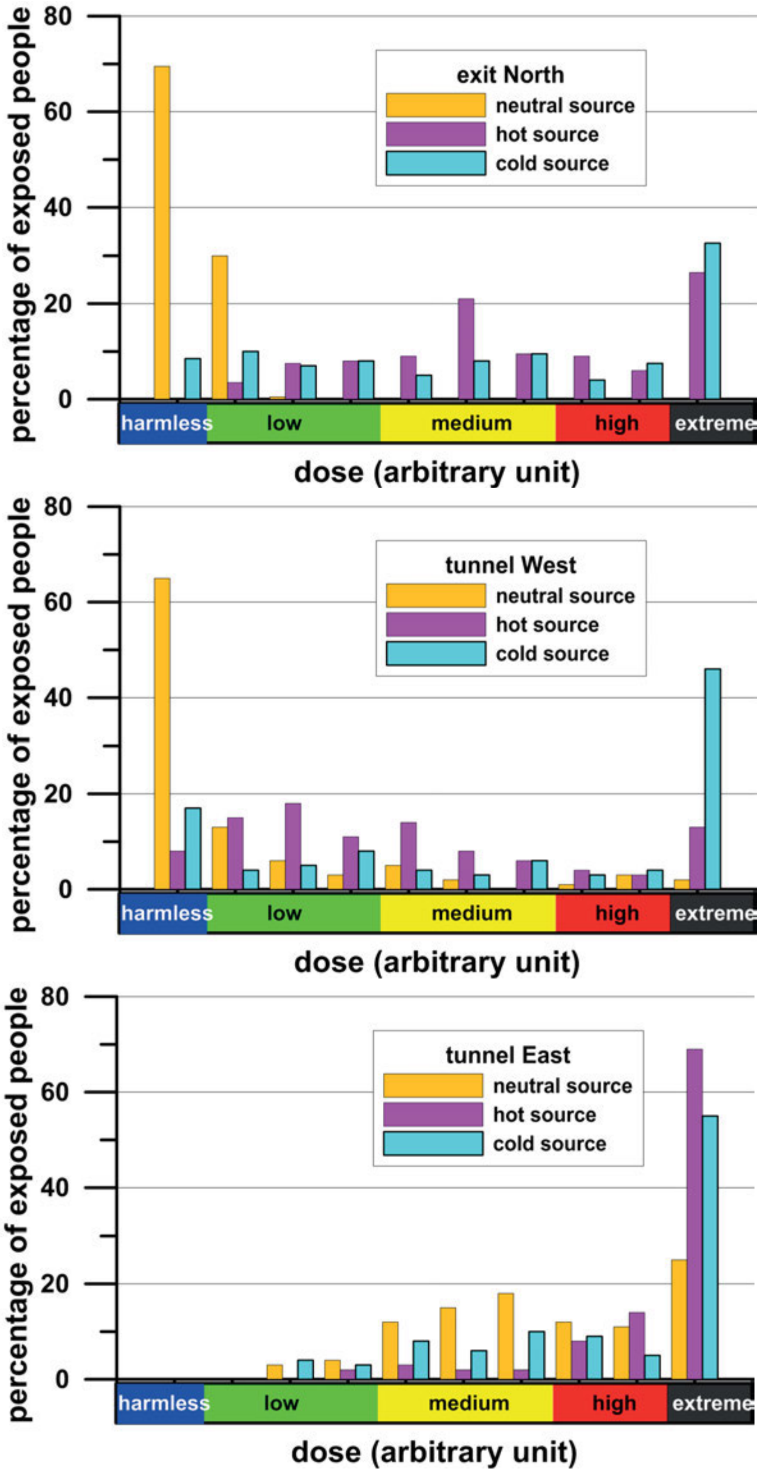

Figure 10: Percentage of 400 agents with a dosage of different health effects for various evacuation routes.

parts of the station and to street level. On the other hand, cold pollutants strongly contaminate the platform, stairs, and tunnels.

However, all the underground facilities are also possible evacuation routes in an emergency situation. In order to guide passengers and staff safely through the station to a secure exit, information about the distribution of hazardous material is necessary. The degree of contamination of people in the metro system depends on meteorological conditions, source characteristics, and also on the actual capacity of the station. An agent-based simulation model was used in this paper to estimate the contamination and health risk of a crowd of people for various pollution scenarios. The evacuation time of a station and the amount of heavily contamination passengers depends strongly on the number of people in the subway. It has been demonstrated that safe evacuation routes cannot be indicated in general but depend on the parameters mentioned above.

Although there are numerous unknowns and uncertainties, the model system applied in this study can be effectively used to find bottlenecks and optimise evacuation routes or to recommend locations of fire, heat, or pollutant detectors. The air pollutants released in the underground will after a while also find their way to street level. Since the model system calculates the above-ground as well as the underground situation, valuable information about the local exposure to hazardous material in the building environment at street level is available for the rescue units.

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