Towards a dynamic evacuation system: developing methodologies to simulate the evacuation capabilities of subway stations in response to a terrorist attack with CBRNE weapons

James Charlton[1], Markus Brune[2]
[1] University of Northumbria, Newcastle upon Tyne, United Kingdom [2] Department of Geography, Ruhr-University of Bochum
[1] j.charlton@northumbria.ac.uk [2] markus.bruene@rub.de

Events in recent times have highlighted the vulnerability of underground public transportation to possible terrorist attacks. A key question therefore is how an evacuation can be accomplished from underground stations safely. The strategy "go up and take the nearest exit to the surface" might not be the best response. Evidence from the Daegu subway station fire in 2003, investigated by Tsujimoto (2003) and Jeon and Hong (2009) establish that smoke or toxic airborne substances from a terrorist attack tend to use the same direct routes used by the fleeing passengers and as result significant injuries or fatalities can occur. This study proposes the concept of a dynamic evacuation system which would guide subway users along safe routes. To test how this system may operate, the study discussed combines measurements from tracer gas experiments with climate measurements to establish how toxic agents spread in subway stations under certain conditions and combines these results with those from pedestrian simulations applied to calculate evacuation times for possible escape routes. By integrating the resulting dataset from these methods, an evidence base of how a dynamic evacuation system may work can start to form.

Keywords: *pedestrian simulation, subway climatology, CBRNE, subway evacuation, tracer gas experiments*

INTRODUCTION

This paper introduces an initial strategy to aid in the evaluation of different evacuation procedures for subway stations in response to a terrorist attack with chemical, biological, radiological, nuclear and explosive (CBRNE) weapons. The paper introduces the individual strands of research (subway climatology, tracer gas experiments and pedestrian simulations), to highlight the development and application of the proposed methodologies to develop an understanding of how effective a dynamic evacuation system may be. The study discussed, demonstrates that by integrating appropriate datasets a greater understanding of the impact of different evacuations routes on an evacuees health can be understood. It is shown that by controlling the routes pedestrians use to exit a subway station, the number of fatalities can be reduced. It is highlighted that a dynamic evacuation guiding system based on subway climatology would take into account the location and cause of the evacuation, the resulting dispersal of gas, smoke, etc. and the subway climatology at the time. In doing so, the system could identify the most endangered areas and guide passengers via an adaptive escape route using audio and visual techniques. Information on the evolution of the emergency situation could also simultaneously be relayed back to the rescue forces to help plan the rescue and evacuation procedures, by being able to answer questions as to where to concentrate the rescue teams. It is envisaged that such a system would help to plan the rescue and evacuation procedures by identifying areas to concentrate the rescue teams, identifying the most endangered areas and providing an adaptive escape route system for the passengers. However, before such a system could be implemented, this paper concludes by highlighting the need for further study and how the latest advances in simulation software can further aid in our understanding and prediction of similar situations.

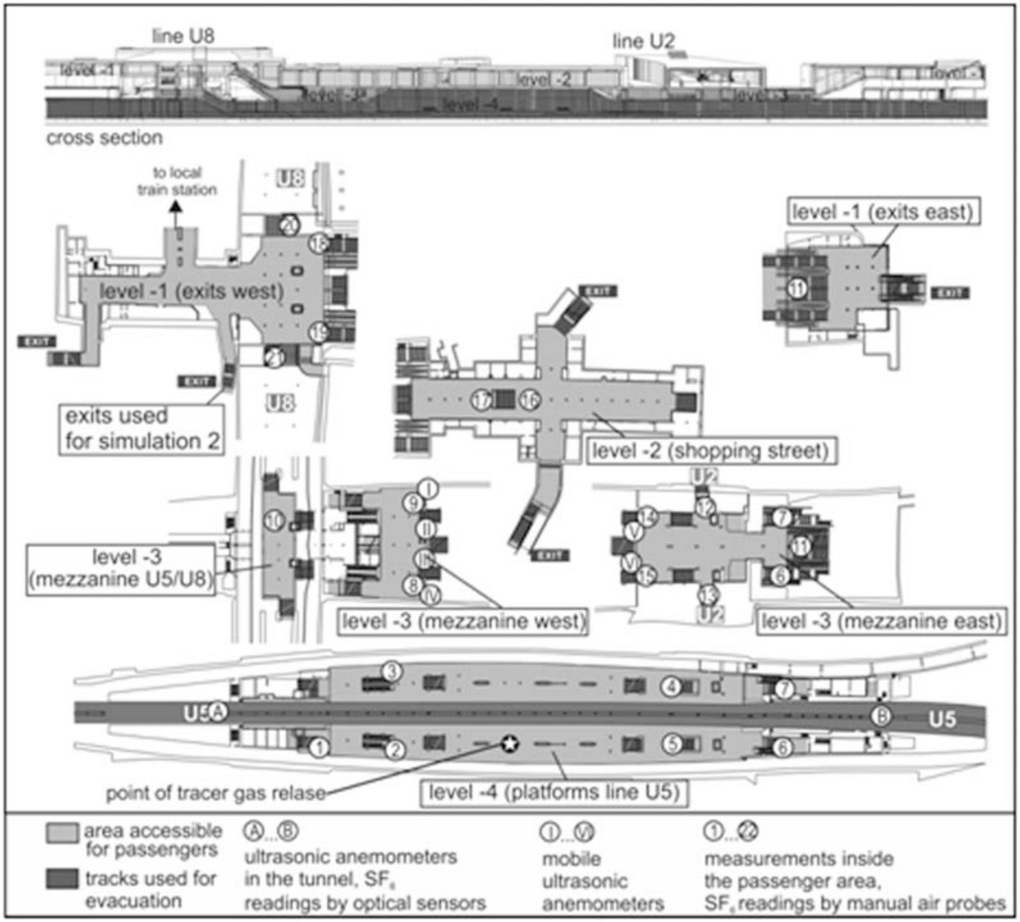
CASE STUDY: ALEXANDERPLATZ, BERLIN.

To aid in development of the proposed methodology this paper highlights the application and results from the assessment of the subway station, Alexanderplatz - Berlin, Germany. The subway station Alexanderplatz (figure 1) is located in the center of Berlin and is the most used interchange station in the city. Built from 1910 - 1913 according to the plans by Alfred Grenander, the underground station originally only consisted of one line. From 1926 to 1930 two additional lines were adjoined, also built according to Grenander's conception. Today the subway station still consists of these three subway lines, the North and South running U2 and U8 and the East and West running U5. Alexanderplatz subway station is also directly connected to a local over ground train station. Due to the importance and complexity of Alexanderplatz, the station has nine exits to the outside, one exit to the local train station and another to an office building. As a result it is an ideal subway station to aid in the development and application of the initial proposed methodology.

STRAND 1. SUBWAY CLIMATE

The relatively young research field of "Subway Climatology" was developed in the late 1990s (Pflitsch and Küsel 2003). The workgroup of Cave & Subway Climatology (Ruhr-University Bochum) investigated the special climate conditions in subways since 2000 (Pflitsch et al. 2010). The BMBF (German Federal Ministry of Education and Research) funded the research projects OrGaMIR and OrGaMIRplus (Cross-organizational hazard prevention to protect human life and critical infrastructures by optimized prevention and reaction) to examine the special climate in subway systems (Blennemann, F, 2005). From this research it was established that the energy budgets of subway stations differ from classical climatology: radiational heating and cooling processes are absent, the soil heat flux is significant higher due to higher surface volume ratio and higher ground temperature in urban agglomerations, anthropogenic energy release from trains, technical equipment and passengers also has to be taken into account. On the other hand energy loss due to latent and sensible heat transfer is highly reduced. These climatic key factors cause a general over-warming of subway tunnels compared to the outer atmosphere from late summer to winter. This effect can become even stronger if a fire breaks out in a station by adding additional heat to the climate. The effect of penetrating cold air and rising warm air at the subway systems openings to the outer atmosphere drives natural air flow in the tunnels. This natural air flow is not stable, different aboveground weather situations leads into alternating air flow direction inside the subway tunnels (Pflitsch and Küsel 2003).Therefore, in the event of a terrorist attack with CBRNE substances inside a sub-

Figure 1
Overview of subway Station Alexanderplatz and positions of measurement points,top: cross section, bottom: plan views. More exits can be found on line U2 and U8.



way station, such climatology would have a major effect on the dispersion of the airborne substances released (Brüne et al., 2012).

Climatology results: Alexanderplatz

In order to gain an understanding of the climatology of Alexanderpaltz, continuous long-term air flow measurements (A, B, figure 1) were set up in the adjacent tunnels of the U5 subway platform as part of the OrGaMIRplus Project. The data gathered, established that when there was no train movement, there was little air movement in the tunnel, allowing thermal effects to dominate; air heated up inside the station and moved due to buoyancy effects to upper levels and to the outside. In addition with the very low airflow velocity at the adjacent tunnels (a and b) it leads to the assumption that released tracer gas would not penetrate the tunnels, but instead rise up to the upper level and find its way through station entrances to the outside.

For the period of the study discussed in this paper, six additional ultrasonic anemometers (I-IV, figure 1) were placed at the mezzanines on level -3 to measure the air flow inside the subway station. Again, the mobile measurements mostly showed up streaming air masses from the U5 platforms (level -4) to the mezzanine west (III) and the mezzanine east (V, VI). The exception to this was at location IV on the mezzanine west. At this location cold air penetrates from outside, therefore downstream airflow was recorded.

STRAND 2. TRACE GAS METHODOLOGY

To aid in the simulation of a terrorist attack with CBRNE weapons, sulphur hexafluoride (SF6) was used as a tracer gas to exanimate the behaviour of airborne substances. SF6 is nonvenomous, non-smelling, non-visible and easily detectable due to its very low occurrence in the atmosphere of 0.005 ppb. Although sulphur hexafluoride is initially six times heavier than air, on release it mixes very quickly with the ambient air and behaves like it (Pflitsch et. al., 2010). Sulphur hexafluoride can therefore be considered as an appropriate safe gas to simulate a terrorist attack with CBRNE weapons.

In the development of the proposed strategy the release of the tracer gas took place outside of operational hours in order to replicate best practice, where ventilation systems are switched off in the event of a fire or terrorist attack. Sanchez et. al. (2000) modelled the number of victims associated with a terror attack using chemical or biological weapons and concluded that the best strategy is to shut down the ventilation and stop the trains. Similarly many old subway stations do not have ventilations system at all. So the operational break in which the tracer gas simulations were carried out, reflects the response of subway operators to the hazardous circumstances resulting from a CBRNE attack. Furthermore, turning the fans off allows subway climatology to play the leading role in the movement of the gas throughout the station. Therefore the empirical dispersion of tracer gases obtained from this study can be used to accurately analyse the evacuation simulations.

During the study an amount of 4kg SF6 was released for two minutes in the middle of the U5 platform. In different locations students (1-22, figure 1) took samples every minute with 60 ml syringes. The syringes were closed with a rubber plug and the air was examined by gas chromatography afterwards.

Results from Tracer gas dispersion

Following the release the gas the first high values were observed only 4 minutes at measurement point 8, located in the mezzanine west, with a reading of 1090 ppb (see figure 2). At the same time a greater contamination reading was recorded in the above lying shopping street level at measurement point 16, with a reading of 6630 ppb. In the remaining areas of the subway station, including the lowest level (level -4) where the gas was released, readings lower than 1000 ppb were recorded for a period up to 6 minutes following the start of the release. After this period of time, significantly high reading were recorded for measurement points 5 and 14 located on level -4 and the east mezzanine level -3, respectively. These values stayed high for the remaining experimental time. In contrast, over a similar time frame, recordings at measurement points 8 and 16 began to decrease. Recordings at measurement point 16 gradually decrease from 5 minutes after the release, while recordings at point 8 remained high before more dramatically falling after 11 minutes. The initial lack of build-up of tracer gas on level -4 is believed to be related to the dimensions of the space. The ceiling of platforms U5 is more than 5m high and at its widest spot measures 36m.

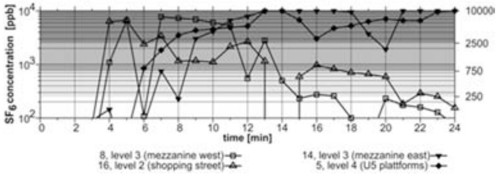


Figure 2
Timeline of SF6 Values of selected Measurement points.

Summarizing the tracer gas readings, during the first 5 minutes gas rises from the lower level through the western mezzanine into the shopping street level. After this period the trajectories moved to the eastern part of the station and the concentration remained high. Both pathways lead to the shopping street where high concentration could also be found.

STRAND 3. PEDESTRIAN SIMULATIONS

To examine the evacuation capabilities of Alexanderplatz, the study adopted the use of agent based pedestrian simulation software capable of representing the attributes and behaviour of individual agents within given environments. The selected software, Legion SpaceWorks, allows entities to be programmed to have; varying degrees of prior knowledge regarding a buildings layout (e.g. commuters vs. tourists), different mobility (e.g. children, adults, impaired, runner, etc.), or different global origins (e.g. UK, Asia, North American, etc.). All of these varying options and interactions define the speed and route in which agents will navigate through a space. Primarily used by architects and civil engineers, unlike its predecessor Legion Studio, Legion SpaceWorks does not require the user to define the paths they take, but instead to only define the origin and exit points of agents. Route modifiers are then added to the model to trigger a change in the movement, activity or destination of the pedestrian, allowing for a more organic and realistic pedestrian flow to be achieved. Using these available options and 2D CAD plans of each platform and concourse area within the station Legion SpaceWorks was used to create evacuation simulations of Alexanderplatz.

For the study discussed, it was assumed that 2050 agents were at their starting position at the lowest level on line U5, this represent the highest demand according to the German Railway Authority, the other subway lines where neglected. Of the 2050 agents placed throughout level -4, 236 agents were located on each platform, distributed as shown in Figure 3, and 789 agents were distributed evenly throughout each of the trains. The speed profiles for each of the agents were configured to represent Northern European commuters. The agent's reaction time to an alarm sounding were defined in accordance with British Standards for a transportation hub (British Standards Institution, 2004) which refers to six key categories of fire evacuation analysis; alertness, familiarity, building type, staff training and alarm type. In accordance with these guidelines, in each of the scenarios simulated, no agents reacted to the alarm sounding in the first 90 seconds, the majority of the agents reacted around 165 seconds and all agents had reacted within 240 seconds.

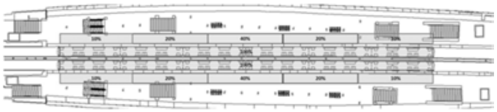


Figure 3
Percentage distribution of agents within the pedestrian simulation model (Level -4)

Results from pedestrian simulations

Two different multi agent pedestrian simulations were set up:

- Simulation 1: The agents have free choice to find the shortest route
- Simulation 2: Agents were forced to evacuate through the west route only. This decision was based in tracer gas results and should be the most uncontaminated evacuation route.

In simulation 1, where the agents had free choice to find the shortest route out of Alexanderplatz, the simulations showed that the majority of the agents chose to exit using the central stairs at either end of the platform, via level -3 and exiting on level -2 (see figure 4). The agents that chose to exit via the west central stairways were quickly subjected to congestion on level -4, which was sustained for several minutes and spread to the west central stairway located on level -3 as more and more agents tried to evacuate via this route. Following the evacuation from level -4, the agents were able to remain at a consistent speed while exiting the model.

In the 2nd simulation agents were guided along a pre-defined route away from the dispersal of gas. Agents were guided to the relevant stairs at the far west side of level -4. Agents continued up these sets of stairs until they reached level -1 where they were navigated to use only exit Ap III/3 located on the south side of level -1 west (see figure 5). Although this route was chosen to prevent agents exiting via routes highly contaminated with lethal gas, the limited number of exits resulted in high levels of congestion, most significantly for those agents located on platform 2. Agents exiting via the defined route from platform 2 became obstructed by those agents exiting from platform 1. The obstruction resulted in a buildup of agents from platform 2 on the selected stairs ways, resulting in no significant movement from agents exiting from platform 2 for a period of 3 minutes.

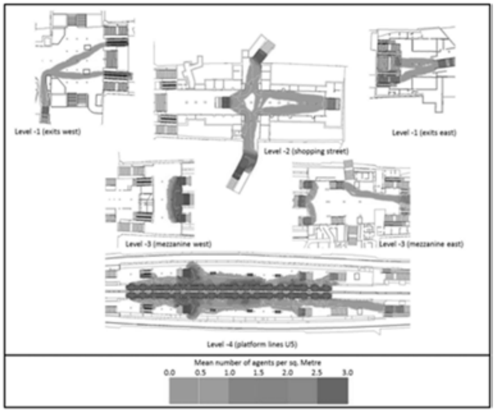


Figure 4
Simulation 1 - Cumulative Mean Density map

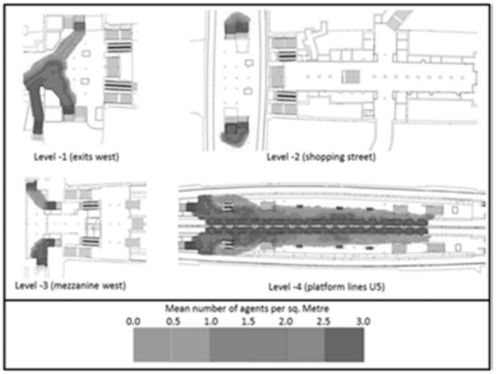


Figure 5
Simulation 2 - Cumulative Mean Density map

The egress times for each of the simulations are summarized in table 1. It is shown that the agents were able to exit Alexanderplatz the quickest when they had free choice to decide to shortest route (simulation 1). Agents were slowest to exit the model when they were guided on a pre-defined path, as in simulation 2. In the 2nd simulation it took 17:05 minutes for all the agents to exit the model, even though the first agents began to exit the model in a comparable time to the agents in simulation 1. This significant increase in time is a result of the congestion caused by agents exiting platform 1 and blocking agents exiting from platform 2, due to the agents only be able to exit via one exit (Ap III/3). The resulting bottleneck caused agents exiting via the pre-defined route from platform 2 to make no significant movement for a period of 3 minutes.

Table 1
Time of egress for different levels subdivided by the two simulations

Table 1: Time of egress for different levelssubdivided by the two simulations

Platform/concourse	Simulation 1	Simulation 2
Level -4	6.23 min	11.30 min
Level -3	7.28 min	12.30 min
Level -2	9.05 min	13.39 min
Level -1	5.37 min	17.05 min
Station (Total)	9.05 min	17.05 min

COUPLING TRACER GAS AND PEDESTRIAN SIMULATION OUTPUTS

From the SF6 tracer gas readings a contamination for different parts of the station could be derived for every minute of the study. Similarly, the pedestrian simulations provide the location of agents every 0.6 seconds. By knowing both the position of each agent and the changing concentration levels of SF6 throughout the station, it is possible to interpolate the amount of inhaled gas by each agent as they move through the model and get a definitive understanding of how each evacuation route would affect the agent's health. In order to get a more realistic assessment of human safety during the evacuation time at this stage of the study it was assumed that phosgene (CClO2) was used instead of SF6. 2.7 kg of phosgene is needed to have the same concentration levels like 4 kg of SF6 (see Table 2).

Table 2
Chemical properties of SF6 and Phosgene and the mass equivalents causing the same concentration levels

Table 2: Chemical properties of SF_6 and Phosgene and the mass equivalents causing the same concentration levels

Chemical properties	SF_6	Phosgene
molar mass	146.05 g·mol^{-1}	98.92 g mol^{-1}
density gas	6.63 kg·m^{-3})^{a,b}	4.53 kg·m^{-3})^{c}
density liquid	-	1.4 g·cm^{-3}
boiling point	-64°C	7.44 °C
EU classification		Very toxic T+
equivalents		
Mass	4.0 kg	2.709 kg
Particle number	27.387 mol	27.387 mol
Volume gas	613,85 l)^{a,b}	613,85 l)^{a,c}
Volume liquefied		1928 cm^3 = 1,928 l
^{a}T=0 °C, ^{b}P=1013 hPa, ^{c}T=15 °C		

Results of coupling outputs

Considering the Acute Exposure Guideline Levels (AEGL) of the US Environmental Protection Agency [10], two values can be used to examine the influence on human health:

- AEGL-2 (600 ppb for a 10 minutes exposure period): is the airborne concentration of phosgene which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL-3 (3600 ppb for a 10 minutes exposure period): is the airborne concentration of phosgene which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

From simply overlaying the outputs from the pedestrian simulation with the contamination maps produced from the tracer gas experiments it is possible to carry out an initial examination into those agents which would have been exposed to high levels of gas. Figure 6 shows the position of the agents from simulation 1 and 2 after 5 minutes, against the corresponding contamination map. It is clear that those agents which have chosen the quickest route (simulation 1) have also moved through the areas of high contamination located on the west mezzanine on level -3 and the shopping street located on level -2.

Based on the results shown, a safety assessment of different evacuations can be made from the total numbers of agents reaching the different levels. Table 3 summarizes these results and indicates the number of agents that exceed the two levels. As expected from the initial examination, in simulation 1 the agents using the west staircases between the platforms U5 and the shopping street begin to exceed the AEGL-2 level when they are on the west mezzanine level. Those agents that are slow to respond and as a result are caught in the congestion that builds on these staircases are also the first agents to reach the deathly AEGL-3 level in this location. As the evacuation continues more deaths are expected on the shopping street level. From the completed

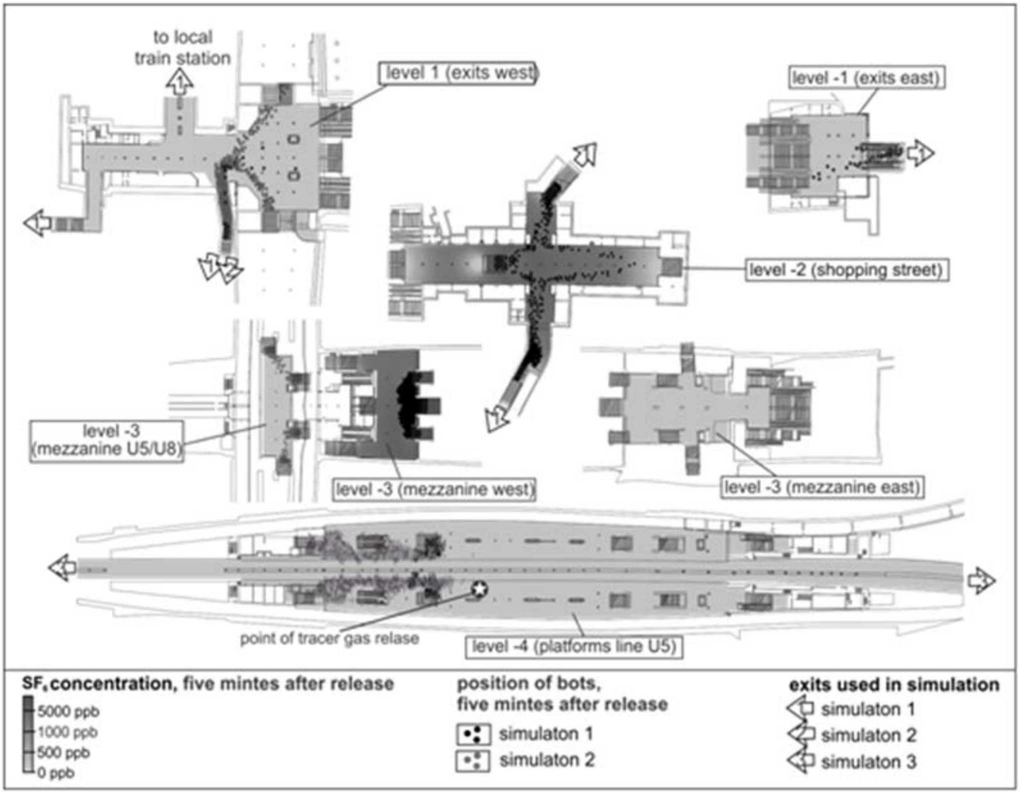


Figure 6
Concentration and position of bots in simulation 1 and 2, 5 min after release and exists used for pedestrian simulations 1,2,3

study, the results show that in simulation 1, 362 agents will die during their evacuation of Alexanderplatz, whilst 1060 will have long-lasting health issues. This study could not take into account that agents who exceed AEGL-2 level of contamination may evacuate slower, increasing the congestions build up and also that dead agents may become obstacles for the other agents. In the 2nd simulation, even with the low contamination, due to the long evacuation time, it was established that 212 agents will exceed the AEGL-2 level before they are able to exit the subway station, but no agents will exceed the AEGL-3 level. The combined tracer gas results and pedestrian simulation shows that all the 212 agents that exceed the AEGL-2 level will do so in the congestion build up on level -1 as they try to exit via a single exit. On this level, there are two more exits available, so the number of harmed passengers would significantly lower.

Table 3. Summary of agents exceeding AEG levels

Concentration	Simulation 1	Simulation 2
< 600 ppb	628	1838
AEGL-2 (>600 to 3600 ppb)	1060	212
AEGL-3 (>3600 ppb)	362	0

Table 3
Summary of agents exceeding AEG levels

In comparing the two simulations it is clear that agents exiting via a controlled, pre-defined route are able to do so in the safest manner, regardless of the increased evacuation time. The results show that the majority of the agents in simulation 2 remained under 600 ppb and no agents exceeded the AGEL-3 level and therefore no agents would have died exiting via this route.

CONCLUSION: TOWARDS A GUIDED EVACUATION SYSTEM

This study aimed to develop methodologies to highlight the advantages a dynamic evacuation system could have on the safety of subway user evacuating subways in response to a terrorist attack with chemical warfare. By combing tracer gas results based on subway climatology with outputs from pedestrian simulations the study established how different evacuation routes have different risk levels. Generally it was showed that staying as long as possible in lower levels or taking guided routes away from the dispersal of gas could be a good strategy to leave the area of risk even if it takes longer. It was shown that the subway climate conditions, especially the airflow in tunnels outlines the basis one element for a dynamic evacuation guiding system, which can be proposed from the results of this study. Such systems would take into account the location and cause of the evacuation, the resulting dispersal of gas, smoke, etc. and the subway climatology at the time. In doing so, the system could identify the most endangered areas and guide passengers via an adaptive escape route using audio and visual techniques. In catastrophic circumstances people want to go out as quickly as possible to the over ground, so intelligent evacuation systems may guide people against their natural flight behavior. Information on the evolution of the emergency situation could also simultaneously be relayed back to the rescue forces to help plan the rescue and evacuation procedures, by being able to answer questions as to where to concentrate the rescue teams.

Although this study made a significant start in developing methodologies and an evidence base for the concept of a dynamic evacuation system, the applied methodologies are still not fully formed to allow for a more extensive study. The tracer gas data presented in this paper is based on a single tracer gas experiment and is only valid for this specific climatic situation. Although this limitation does not distract from the aim of this paper to show how combining results from tracer gas experiments with pedestrian simulations can be used to assess evacuation procedures for underground stations during an emergency situation, it does not allow for other simulations to be executed or for future evacuations simulations to be carried out without first collecting first hand subway climatology results. As such, in order to develop a more sound methodology for a more dynamic study, it can be proposed that a relationship between urban weather trends and subway climatology needs to be established. It is certainly within the scope of accessible simulation software to help establish this trend. In doing so, the climatology of a subway station during a given state of weather could be predicted, allowing for further, dynamic studies, to be carried out.

REFERENCES

Blennemann, F 2005, *Brandschutz in Fahrzeugen und Tunneln des ÖPNV. Fire protection in vehicles and tunnels for public transport*, Alba-Fachverl

Brune, M, Pflitsch, A, Agnew, B and Speigel, J 2012 'Dynamics of natural air flow inside subway tunnels', *Proceedings from the fifth International Symposium on Tunnel Safety and Security*, New York, pp. 329 - 337

Jeon, G and Hong, W 2009, 'Characteristic Features of the Behavior and Perception of Evacuees from the Daegu Subway Fire and Safety Measures in an Underground Fire', *Journal of Asian Architecture and Building Engineering*, 8, pp. 415 - 422

Pflitsch, A, Brune, M, Ringeis, J and Killing-Heinze, M 2010 'ORGAMIR: Development of a safety system for reaction of an event with emission of hazardous airborne substances - like a terror attack or fire - based on subway climatology', *Proceedings from the fourth International Symposium on Tunnel Safety and Security*, Frankfurt au Main

Pflitsch, A and Kusel, H 2003, 'Subway-Climatology - New Research Field for the Management of Possible Catastrophes in Subway Systems', in Pyka, J. L., Dubicka, M, Szczepankiewicz-Szmyrka, A and Sobik, M (eds) 2003, *Man and Climate in the 20th Century*, University of Wroclaw, pp. 384-394

Sanchez, J. G., Coke, L, Wasmar, F and Policastro, A. J. 2000 'Comparison of Strategies in Managing C/B Releases in the Subway Environment', *Proceedings of Tunnel Management: 3rd International Conference*, Sydney
Tsujimoto, M 2003 'Issues raised by the recent subway fire in South Korea', *ICUS INCEDE newsletter: International Center for Urban Safety Engineering*, Tokyo