Review of numerical studies on ventilation systems for subway networks in emergency situations

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Abstract. Since the subway systems are constantly developing at a high rate to cope with the increasing number of commuters, their safety is a great challenge and extensive research was done to fulfil the safety regulations in this field. Numerical modelling represents a modern research method used more frequently in the academic environment over the last decades, being constantly validated through comparisons with results of other classical research methods. This paper presents a thorough analysis of the numerical studies on smoke evacuation in emergency situations from tunnels and subway stations, with a focus on the research concerning the use of platform screen doors (PSD) in emergency situations generated by fires. The numerical simulation software mostly used are Fire Dynamics Simulation and Ansys Fluent (based on Computational Fluid Dynamics modelling technique), their results being extensively compared with experiments and analytical formulae. Since most of the studies focus on determining the specific values of some fire related parameters (critical velocity of the ventilated air, backlayering distance of the smoke, maximum temperature in the smoke layer or maximum concentration of smoke pollutants), a lack of research regarding the efficient use of PSDs concomitant with the ventilation system in emergency mode has been identified.

1. Introduction
Since the first underground line was built in 1863 in London, subway has been implemented worldwide as the solution for rapid transportation within crowded cities and decongestion of urban traffic. The International Associatio\textsuperscript{n} of Public Transport estimated that at the end of 2017, 178 cities from 56 countries used subway transportation, serving in average 168 million commuters every day [1]. According to the same report, since the year 2000 the total number of subway stations increased by 70\%, totaling 13,903 km of railway that serve 11,084 stations. As part of the evolution, the same association published in April 2019 “The world report on metro automation” [2], presenting that in 2018 automated metros reached the 1000 km milestone with the opening of the Pujiang Line in Shanghai. As of December 2018, nearly a quarter of the world’s metro systems have at least one fully automated line in operation, a 27\% increase since 2016.

Having in mind the great number of daily users, safety issues arise in this closed environment. Incidents can be caused by the malfunctioning of traffic managements systems, fires due to technical errors or arsonists and terrorist attacks. The number of victims caused by terrorist attacks only since 1960 is more than 2000 dead people and 13500 injured [3], most because of the fire that follows the attack or the high concentration of poison spread in the station. At the New York metro, according to
the Metropolitan Transportation Authority annual report, the number of fires rises up to 963, out of which 698 are fires on the tracks [4]. In order to protect the people inside the metro system in case of emergency situations generated by fire, the ventilation system has to be constantly adapted to work efficiently with other additional protective measures, such as the platform screen doors (PSD).

The platform screen doors are installed to create a barrier between the tunnel and the station. If they do not cover the whole distance from the floor up to the ceiling, they are known as platform edge doors (PED). The first PSDs were built in Saint Petersburg Metro Line 2 between 1961 and 1972, as actual openings in the station wall that supports the ceiling of the platform. The first subway system that installed the transparent PSDs for reasons other than architectural constraints was the Singapore MRT in 1987, namely for climate control and safety reasons [5]. Since then PSDs have gained popularity and have been installed in subway stations all over the world for their advantages. For example, according to Chung et al. [6], the number of suicides in the South Korean subway system dropped by 89% in 2016, after the installation of PSDs. Similar evolution has been recorded in Japan, where the suicides were reduced by 76% after the installation of PEDs [7]. Moreover, the PSDs contribute to the reduction of noise levels in the stations. Soeta and Shimokura [8] found out that the background noise is reduced with 8 dB in the stations where the PSDs are installed. At the same time, they separate the tunnel environment from the platform, thus making possible to maintain the thermal comfort in the station with lower energy consumption [9]. Other research has shown that the air quality on the platforms is improved [10][11], while this may have consequences over the quality of air within the trains [12].

Although much research has been made on fire parameters specific to tunnels (critical velocity, backlayering length, flame length etc.), there are a limited number of studies concerning the use of PSDs in emergency situations generated by fire. Since large scale experiments are difficult to be made in this case, most of the research is based on Computational Fluid Dynamics (CFD) methods, which gained popularity in the academic world in the last decades. This method has been validated through a number of large scale and small scale experiments, conducted by the National Institute of Standards and Technology from USA, and other researchers worldwide [13].

This paper presents a review of the CFD studies on ventilation methods that involve also the use of PSDs to maintain tenability conditions necessary for safe evacuation from the subway stations in emergency situations.

2. Numerical studies on ventilation systems for subway stations and tunnels in emergency situations

The focus of research concerning fire in tunnels is the determination of fire parameters such as critical velocity, backlayering length, flame length, maximum temperature under the ceiling or toxic gas concentrations.

Critical velocity is the longitudinal ventilation velocity necessary to prevent upstream movement of combustion products, while the backlayering is the length of the reversed smoke flow upstream the fire when the ventilation velocity is lower than that of the critical velocity [14].

Haddad et al. [14] conducted a thorough review of the research on these two parameters, presenting the main results from small scale experiments and theoretical analysis on this matter.

Hu et al. [15] conducted four full-scale experiments in a road tunnel and then compared the results with the results of the CFD simulations, showing that the CFD predicted results for critical velocity and backlayering were very close to the full-scale data, with a deviation of only 40% of the predicted temperature at distances higher than 80 m away from the fire.

David Purser used numerical analysis to determine the conditions inside the Mont Blanc tunnel during the fire in 1999 [16]. The initial conditions used for the numerical analysis were taken from the full-scale experiments that were conducted in the same tunnel a few years before. The numerical results were then used to estimate the time until the conditions in the tunnel became untenable. A “Fractional Effective Dose” (FED) analysis was then carried out to predict the time to incapacitation and death for tunnel occupants related on their location within the tunnel. The effective dose of a
pollutant or an irritant is the threshold concentration or exposure dose at which serious effects are predicted. The FED is calculated taking into account the time of exposure necessary for incapacitation or death and the actual time of exposure to the asphyxiant/irritant [17]. The outcomes of the study provided a validation for the CFD and FED analysis, confirming that the numerical studies can be used to successfully describe the fire evolution in the tunnel.

Weng et al. [18] conducted a study on the critical velocity in a sloping tunnel fire under longitudinal ventilation and introduced a sectional coefficient to describe the tunnel cross section, and then used it in dimensionless formulae for backlayering and critical velocity. The results of these formulae were then compared with the results of 250 CFD simulations based on nine typical tunnels geometries and 45 small-scale experiments carried out in a 1/10 scale model tunnel, with slopes between -3% and 3%, all research methods showing appropriate results.

Vauquelin and Wu [19] used CFD simulations to carry out experiments with higher values of the heat release rate than those possible to be obtained in the small-scale experiments. The results of the simulations also showed the smoke movement within different tunnel geometries generated by variable aspect ratio of the tunnel. The numerical analysis was therefore used as a tool to study fire parameters for conditions that cannot be obtained in small scale experiments.

Wu et al. [20] used CFD modelling to study the smoke temperature beneath the ceiling in an atrium-style subway station by considering different fire source locations. The results of the simulations were validated by three theoretical models developed by Alpert, Heskestad and McCaffrey, each one of them adapted to a different space geometry and fire location.

Numerical simulation has also been used by Zhang et al. [21] to study the effect of tunnel curvature on critical velocity and backlayering, showing that these fire parameters are strongly influenced by the tunnel radius. The CFD results were in line with the results of the analytical formulae proposed by the authors.

Huang et al. [22] used CFD modelling to study the air velocity through the ventilation ducts of a subway tunnel. They proposed a new ventilation method for a double track subway tunnel based on combined ventilation ducts that proved to have a smaller ventilation velocity than individual ventilation ducts for each tunnel track. The conclusions were based solely on numerical analysis with no other type of validation.

Kazemipour et al. [23] studied the fire consequences on ventilation equipment performance via numerical experiments. For this reason, they conducted two series of simulations, with jet fans located only upstream the tunnel fire and with jet fans positioned in the smoke, close to the fire location and then compared the results with the data collected from tunnel full-scale experiment, showing a very good agreement within 5-15% accuracy.

A series of full-scale numerical simulations were carried out by Shaogang Zhang et al. [24] using Fire Dynamic Simulator (FDS) to investigate the smoke back-layering length in subway tunnel with different train lengths and longitudinal ventilation velocities. The simulation results indicate that the train length has a great influence on the smoke backlayering that shouldn’t be ignored. A global correlation model was proposed based on dimensionless analysis and simulation results.

Limao Zhang et al. [25] developed a systematic hybrid approach that integrates available safe egress time, required safe egress time, numerical simulation and multi-attribute decision analysis to support fire safety risk assessment in a subway station. In order to discover the worst fire scenarios, they conducted four numerical simulations with different heat release rate and fire locations, therefore numerical modelling served as an important tool in the overall risk assessment.

Two studies realised by Gao et al. [26][27] used CFD analysis to evaluate the effect of hybrid ventilation on CO reduction, its effect on suppression of horizontal dispersion of smoke and the influence of the hybrid ventilation system on smoke elimination. The numerical results were validated through a small-scale experiment described in the second study [27].

Guo and Zhang [28] proposed a new critical velocity analytical formula for tunnel fire under longitudinal ventilation and compared the result with small scale experimental data and the results of CFD simulations from two different software. The results of this cross examination proved to be in
good agreement with each other, confirming the same trend of variation for critical velocity versus fire size.

Weng et al. [29] used dimensional analysis to determine the expression of critical velocity and backlayering length and then validated the formulae through small scale experiments and CFD analysis. After the first numerical model showed good agreement with the experimental results, the model was used to study nine different geometry configurations, proving once again that the numerical simulation is a versatile study method.

Numerical studies can also be realised at reduced scale, as is the case of the study conducted by Harish and Venkatasubbaiah [30], who simulated different fire scenarios in a 1:6 subway tunnel. Because they studied the performance of natural roof ventilation and the way it influences the fire flow characteristics, they simulated geometries with single or multiple roof openings and varied the vent size and fire source locations, concluding that the ceiling openings are effective in ventilating the hot gases and reduce the longitudinal smoke velocity.

Numerical analysis offers the great advantage that it can study fire evolution and smoke propagation in complex geometries. Lee et al. [31] carried out numerical simulations to analyse the way that smoke extraction systems and fire shutters work to ensure a safe environment in subway stations in case of a kiosk fire on the underground platform. Six square methanol trays with a heat release of 80 kW were used in the real subway station to study the distribution of temperature, velocity and static pressure. The results of these field measurements were in good agreement with the results of the CFD simulations. Since this value of heat release corresponds to an initial stage of a fire, numerical modelling was used to simulate fully developed fire and its effect of the smoke extraction system.

Another study that investigates the fire development in a subway station, experimentally and numerically, is the one carried out by Yucel et al. [32]. The experimental measurements were made on 1:100 station scale model and they matched with the CFD simulation results. The authors found out that the maximum temperature in the station, right above the fuel pool, is obtained with an increase of the tunnel longitudinal ventilation velocity from 1 m/s to 3 m/s and without the piston effect generated by the subway entering in the station.

One of the biggest tunnels used for experimental purposes is the Memorial Tunnel (853 m), where 98 full-scale fire ventilation tests were carried out to analyse fire incidents inside road tunnels. Vega et al. [33] reproduced the tunnel using a CFD software and compared the numerical results of three tests involving three different longitudinal ventilation strategies with the experimental results of the same strategies tested in the real tunnel. The CFD model was not very comprehensive (it did not take radiation into consideration), but a good agreement was achieved between the simulated and the experimental results. Even if the experiment involved a road tunnel and not a subway tunnel, it is still a solid proof that CFD simulations are reliable in tunnel ventilation studies.

Teodosiu et al. [34] studied the ventilation efficiency of the system formed by a mid-tunnel fan plant located in a separate construction and the mechanical ventilation from the stations. The scenario involved a train on fire stopped in the tunnel and required immediate evacuation of the passengers. The analysis was realised solely in CFD and concluded that the evacuation towards the nearest station is not disturbed by high temperatures or poisonous CO2 concentrations.

Altay and Surmen [35] set-up a CFD study focused on the effect of blockages in the tunnel over the ventilation critical velocity and temperature distribution. For that reason, they studied three different cases, first one with the fire source in the tunnel but with no blockage, the second one with a blockage located in the upstream of the fire source and the last one with a blockage located in the downstream of the fire source. The first simulation generated a critical velocity of 0.67 m/s, in line with the results presented in literature, while the results obtained from the other two simulations were 0.77 and 0.75 m/s, respectively. The authors concluded that some fire parameters like the heat release rate and the cross-sectional area of the tunnel are influenced by the shape, size and relative position of the blockage.
A special tunnel geometry was studied numerically and experimentally (small scale tests) by Guo et al. [36], who studied the impact of a single-track tunnel or a double-track tunnel over the tenability criteria in case of a train fire in the tunnel. In addition, the tunnel had positive inclination for approximately half of its length (+28 ‰) and negative inclination for the other half (-28 ‰), a specific characteristic that influences the smoke propagation. Both experimental and numerical studies showed that the best evacuation conditions in case of fire in this tunnel are ensured in the double track tunnel.

Zhang et al. [37] focused their attention on the air velocity of the platform exhaust system in case of fire. They realised multiple numerical simulations with air velocity ranging from 3 m/s to 10 m/s and observed that the best results are obtained at 8 m/s. Higher velocities did not generate more significant results and lower velocities did not ensure an efficient smoke evacuation. The numerical results were validated by a full-scale experiment in a subway station on two levels.

As a conclusion, all the articles mentioned above involve numerical analysis as a research tool to study the specific parameters of fire in subway tunnels and stations. Some of them use numerical simulations as the main study tool and try to validate the results through theoretical analysis, small scale experiments or full-scale experiments, while other studies resort to numerical analysis in order to compare the results previously obtained by other means and have a better visualisation of them.

Regarding the software used for these numerical studies, approximately 73% use Fire Dynamics Simulation, while 28% are based on Ansys Fluent (article [26] used two different numerical simulation software and compared the generated results). Half of them do not present a validation method, 23% of the studies validated the numerical results through small scale experiments, 17% used full-scale experiments to validate the results and 12% are compared with the results of theoretical analysis. The most frequent used turbulence model is Large Edy Simulation (LES), in approximately 73% of the articles, while standard K-ε model is used in 23% of the studies and RNG K-ε in 12% of the studies. Only 50% of the studies integrated a radiation model into the simulation and 67% have the mesh grid checked before running the analysis. As far as the geometry is concerned, 45% of the studies are based on a subway tunnel geometry, while the rest of them focus on subway platforms and stations.

3. Numerical studies on smoke evacuation from subway stations equipped with platform screen doors

The purpose of research in this field is to find the best solution to slow down or impede the fire from generating untenable conditions that could affect the safe evacuation of passengers from subway stations equipped with PSDs. Having in mind that every subway station is different, it is almost impossible to find a general solution for the design of the mechanical ventilation system and PSDs; therefore it is important to study the efficiency of the proposed ventilation solution involving the opening/closing of the PSDs for each particular case.

A numerical study comparing the smoke evacuation system of a subway station with or without PSDs has been carried out by Chen et al. [38]. The authors ran a number of CFD simulations to verify the efficiency of the smoke control scheme that is in place in a real subway station, and then proposed a different smoke control technique that involved the opening of a particular number of PSDs close to the fire in order to enhance the suction force of the track ventilation fan. The results showed that the proposed smoke evacuation scheme is more efficient than the one in place.

Another comparative study, but this time between PSDs and PEDs impact on smoke propagation, was realised by Meng et al. [39]. They have studied, experimentally (small scale) and numerically, the maximum smoke temperature and the longitudinal temperature distribution beneath the tunnel ceiling in case there is a fire inside the train. They concluded that the PEDs generated lower maximum smoke temperature and faster longitudinal temperature decay due to the fact that the effective width of the tunnel ceiling is increased, and smoke transfers more heat to the ceiling.

One more study comparing the PSDs and PEDs is the one published by Meng et al. [40]. Using numerical simulation, they have studied the effectiveness of different ventilation modes in case of train fire in a subway station equipped with PSDs or PEDs. Results show that it is better to activate the
lobby air supply system, the platform exhaust system and the over the track exhaust system, while deactivating the under platform exhaust system and the platform air supply system. The optimization strategy is similar for PSDs and PEDs if smoke curtains are used together with the PEDs to stop the smoke from spreading on the platform.

The effect of PSDs on mechanical smoke exhaust system of a subway station was also the objective of Li and Zhu [41]. In their study, the fire starts on the middle of the platform and the results of the numerical analysis indicate that the open PSDs on both sides of the platform improve the efficiency of mechanical smoke exhaust system and reduce the temperature on the platform, making therefore better condition for a safe evacuation of the commuters.

Hu et al. [42] investigated the most effective cooperation mode of the tunnel rail track exhaust system and the platform ventilation system for a scenario involving a train on fire stopping beside the platform. The rail track and the platform are separated by PSDs, but considering the scenario and the need to evacuate the passengers from the train, the doors are permanently opened in the simulations. The authors analysed and compared the distribution of smoke temperature and visibility on the platform and concluded that the best solution is to activate the over track exhaust system and the smoke exhaust system of the platform, while deactivating the under-platform exhaust system.

Wang et al. [43] studied the effect of PSDs on smoke evacuation in case of fire on the platform. For this reason, they tested 24 switch modes of the PSDs, correlated with different fire locations on the platform and different mechanical smoke extraction operating modes. At the end of these numerical simulations they presented bespoke solutions that can be implemented depending on fire source location and fire evolution stage.

The direct influence that PSDs have on the evacuation time was studied by Roh et al. [44] for a subway station on three levels. They performed fire and evacuation simulations to estimate the effect of PSDs and ventilation on passengers’ life safety in a subway train fire and concluded that the available evacuation time is increased with 350 seconds if PSDs are used, compared with the opposite scenario. The available time for evacuation is considered until the untenable condition are obtained on the evacuation paths.

Concerning the use of PSDs on natural ventilation strategies, Wu et al. [45] concluded that in order to strengthen the stack effect in the subway station and to form the optimal smoke flow paths, all PSDs have to be closed. This because, otherwise, the negative pressure needed in the platform smoke layer is decreased by the excessive supplied air from the tunnel and the stack effect is diminished.

Jung et al. [46] performed a numerical analysis of the optimal smoke control and heat removal system operation in a subway station equipped with PSDs. They analysed eight scenarios by changing the operation conditions of the fans for each area and the status (open or close) of the PSDs and concluded that the flow of heat and harmful gas can be controlled by the operating conditions of the fans and the PSDs in the underground subway station.

As a conclusion on this topic, in the literature a small number of articles focused on smoke evacuation from a subway station equipped with PSD/PED systems have been identified, most of them being based on numerical simulation as the main study technique.

The most commonly used software for this purpose is Fire Dynamics Simulation (7 out of 9 articles), using a structured mesh and LES turbulence model. More than half of these numerical studies are not validated at all, two studies compare their results with the results obtained from analytical formulae and one is validated by the results obtained through a small scale experiment.

4. Conclusions
Numerical analysis is a very useful research method especially when experiments require special conditions to be put in practice (large underground constructions with complex ventilation systems, almost permanently used by passengers). Having in mind that the numerical results have been constantly validated by full scale and small scale experiments and they are also in line with the analytical solutions, they can be used for further studies in the field of fire safety design of public buildings.
Many numerical studies have been performed to study the parameters of fires in tunnels, since the results are useful for improving the fire safety measures (concerning the smoke ventilation in emergency situations) in a large number of applications like trail tunnels, auto tunnels, metro tunnels etc.

At the same time, relatively little research has been found in the literature on smoke evacuation from subway stations equipped with PSD/PED systems. Nevertheless, more effort has to be put into this field since the number of modern subway networks equipped with PSD/PED systems is constantly growing worldwide. In addition, problems associated with fires or other unhappy events in subway systems can generate a large number of casualties. Therefore, the solution based on PSD/PED systems can significantly help in these situations.

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