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Bibliographic study: technical prescriptions, norms, national and international standards regarding the safe operation of subway networks. Research on efficient solutions for ventilation systems and PSD / PED systems for subway networks in various emergencies

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1. Introduction

Given the universal demographic trend of population transfer from rural to urban areas, large cities are becoming more crowded each year. One of the major urban problems strictly related to this large influx of people is domestic transport, which is not developing at the same pace as the number of passengers. As a result, public transport is constantly congested and passenger safety issues are becoming more and more pressing.

In this context, the fastest mean of urban transport remains the metro, which justifies the continued development of global metro networks. Thus, from the first metro line built in London in 1863, (the locomotives of that time were powered by steam engines, and the tube tunnels were equipped with powerful fans, which removed the smoke from burning coal and steam directly into the city), the situation evolved in such a way that at the end of 2017, according to UITP official data - "*L'Union internationale des transports publics*" (International Association of Public Transport), the metro systems developed in 178 cities in 56 countries, transporting an average of 168,000,000 people in one day [1]. The accelerated development of metro networks in recent years is best highlighted by the following data: since 2000, 75 new metro networks have become operational, which means an increase of 70% [1]. Basically, on December 31, 2017, the 178 subway networks had 642 lines, with a total length of 13,903 km, serving 11,084 stations [1]. It should also be noted that there are currently cities with subway systems exceeding 2,000,000,000 passengers per year (Tokyo: 3,463,000,000; Moscow: 2,369,000,000; Shanghai: 2,044,000,000) or approaching this number (Beijing : 1,988,000,000; Seoul: 1,885,000,000; New York: 1,806,000,000) [1].

On the other hand, this high density of passengers in metro stations and trains translates into particular problems in terms of ensuring their safety. In general, there are three major categories of serious incidents in subway networks that can have dramatic consequences: technical problems or related to traffic management (which can lead, for example, to accidents between subway trains), people who have fallen on tracks for various reasons and fires/explosions caused by technical problems, respectively by intentional (terrorist) acts.

A general statistic worldwide that comprehensively lists all such events that take place in subway networks is very difficult to perform. However, regarding the number of incidents on the Bucharest subway, a balance can be established for the period 2010–2017, which shows that 27 events took place, as follows: 9 accidents with people who fell on the tracks of which 3 resulted in the death of persons, 8 suicides, 7 suicide attempts, 1 murder, 1 attempted murder and 1 damage to an emergency stop train between 2 metro stations [2]. Also, according to data centralized by the New York subway operator, it appears that the total number of injured people was 172 (of which 58 died) in 2015 and 168 (48 deaths) in 2016 [3].

Finally, at global level, in the last 10 years there have been numerous terrorist attacks on subway systems around the world, events that have killed nearly 90 people and injured about 600 [4].

In this context, it should be noted that in the case of metro networks the worst problems related to passenger safety remain those related to the evacuation of smoke from fires (regardless of their nature) or toxic compounds (chemical or biological). Chen et al. [5] also presents a

centralization of a number of 14 fires that broke out in several subway networks, whose ignition source varies: hot brakes of train sets, defective electrical equipment, transformers, constructions on the waiting platform, electric cables etc. As can be seen, electric fires can have many sources, the consequences being very serious, the most eloquent example being the tragedy in the Baku subway (Azerbaijan) in 1995, where almost 300 people lost their lives [6]. Intentionally caused fires can also have dramatic consequences, with the case of the arsonist of the subway train stopped at Jungangno station in Daegu (South Korea) in 2003, resulting in almost 200 casualties and more than 150 injured [7]. Toxic substance attacks are another serious threat to subway networks, the most publicized example being the sarin gas attack on 3 subway lines in Tokyo (1995), which killed more than 10 people and injured about 1,000 others (of which over 50 very severe) [8].

Basically, direct exposure to fire is not the main danger to the lives of passengers on subway networks in case of fires, but the inhalation of toxic substances contained in the smoke resulting from these fires. It has been shown that in the case of subway fires (trains, tunnels or stations) there is a lot of toxic gases released due to incomplete combustion of various materials [9].

In these conditions, there is currently a lot of research on the implementation of solutions to reduce as much as possible the number of victims in case of unfortunate events in the subway networks. It is noted that the studies carried out focus on improving the efficiency of existing ventilation systems in the event of an emergency, as well as on proposing innovative, high-performance ventilation system solutions. It is also exploring ways in which these emergency ventilation systems can be coupled with other systems that lead to increased safety in the operation of subway networks. Such a system, which allows to reduce the number of accidents and improve the evacuation conditions in case of fire, consists in the installation of automatic protection doors, known in the literature as *PSD* - platform screen doors or *PED* - platform edge doors, depending on the constructive type (the *PED* system is similar to the *PSD* system, only it does not reach the height of the ceiling). These systems create a physical barrier between the platform of the metro station and the train lines, thus reducing the risk of injuries through direct contact of passengers with the train, as well as the penetration of various objects on the train lines. Also, by developing strategies/operating scenarios for these systems, coupled with ventilation (scenarios that consider the positioning of the fire source), it is possible to control the spread of smoke and its correct evacuation, to limit the number of people affected and at the same time facilitate the intervention of rescue teams.

2. Standards for the safe operation of metro networks

2.1 National standards

In Romania, the legislative framework that regulates the fire safety of constructions consists of *Law no. 307/2006 on fire protection* [10] and *Order of the Minister of Administration and Interior no. 163 of February 28, 2007 for the approval of the General Norms for fire protection* [11]. To these are added several technical regulations and fire protection measures specific to different areas of activity.

Regarding fire safety in subway stations and tunnels, this is regulated by the *Order of the Minister of Public Works, Transport and Housing no. 1065 of 30.07.2002 for the approval of the technical regulations "Normative for the design of specific subway constructions and installations regarding fire prevention and extinguishing", indicative NP 071-02* [12] and *Order of the Minister of Transports, Constructions and Tourism no. 1287 of 10.08.2006 for the approval of the Norms for fire prevention and extinguishing, endowment with technical means for fire prevention and extinguishing and rescue of persons, specific to the Bucharest Metro Transport Company METROREX - S.A.* [13]

2.1.1 Normative NP 071-02 (2002)

This standard sets out the performance levels for fire safety of underground subway buildings and installations and is intended for designers, executors and project verifiers, technical experts and execution managers, the owner and user of buildings, and public administration bodies, according to obligations and responsibilities incumbent on them in accordance with the legislation in force.

The normative regulates the performance criteria and general performance conditions of underground subway constructions, ways to limit the spread of fires, smoke evacuation, fire compliance of buildings, escape routes, access and intervention, as well as minimum safety conditions in design and operation electrical installations, fire-fighting installations and fire-signalling installations.

Regarding the smoke extraction installations, the norm specifies that in the underground spaces related to the subway constructions, the smoke and hot gas evacuation is performed with mechanical ventilation installations in depression, the compensation air being ensured by gaps provided with frames with fixed blinds and wire mesh frames.

In the event of fire in tunnels or subway spaces, the smoke is evacuated in the opposite direction to the movement of passengers on the shortest road, so that they have fresh air in front of them.

The equipment that makes up the ventilation units is arranged in specially designed rooms, separated from the rest of the construction according to the provisions regarding the minimum fire resistance of the walls.

The ventilation plants are located as follows:

- minimum one ventilation plant for each subway station;
- one ventilation plant at each interstation, located according to the concrete conditions in the field; preferably in the middle of each section of tunnel between two stations (interstate);

- at least one central for each parking space or depot.

When the parking spaces of the metro trains are arranged in metro stations, the smoke of the respective spaces can be done either independently or through the ventilation plant afferent to the station.

Ventilation plants for stations and interstices are provided with two fans with alternative operation and with the possibility of mutual reservation.

The dimensioning of the ventilation systems, the arrangement of the discharge and outlet openings, as well as the operating schemes to be adopted must ensure the following conditions:

- smoke density should allow good visibility on the escape routes of the people (the smoke density should not exceed 10% up to a height of 2 m from the pedestrian floors);
- velocities of the air currents in the lobby to remove the basket effect of the exits to the outside, above ground;
- the introductions of fresh air and the directing of the smoke to be done in the opposite direction to the movement of the evacuation flows of the persons (the evacuation of the persons to be done in counter-current of fresh air);
- to eliminate the possibility of smoke flooding some parts of the escape routes.

Smoke extraction from the subway stations, as well as from the station-intersection assemblies is provided with axial fans, provided with possibilities to change the direction of rotation in a time interval of up to 3 minutes.

Depending on the number and flow of fans provided and the ratio of exhaust and intake air flow, the exhaust fans must be designed so that they can operate at burning gas temperatures between 200⁰ C and 400⁰ C for at least a period of time equal to the intervention time.

The 200⁰ C value of the smoke and burning gas temperature can be chosen when the fans provide exhaust and inlet flow rates higher than 100,000 m³ / h and are equipped with backup fans.

The starting and stopping of the fans related to the general ventilation is done manually, by local or remote control, from the central dispatcher, according to some predetermined scenarios. In all places provided with controls, the operating status of the fans shall be signalled.

The smoke removal from the commercial spaces is achieved through the general ventilation system of the station.

The smoke removal from the rooms with electric cables is ensured by local fans, with evacuation in the general ventilation channels.

The local fans related to the cable tunnels arranged under the platforms are provided with suction possibilities from the stationary area of the trains.

The other aspects regarding the design and realization of the ventilation systems are solved in accordance with the provisions of the *“Normative regarding the design and execution of ventilation installations”*, indicative I5.

2.1.2 Norms for fire prevention and extinguishing, endowment with technical means for fire prevention and rescue of persons, specific to the Bucharest Metro Transport Company METROREX - S.A. (2006

These rules do not specify information on the design, construction or use of ventilation systems in emergency situations, but rather details on the actions to be taken by Metrorex staff in the event of trains having malfunctions leading to fires. Thus, 3 possible scenarios are described and the actions to be executed in each of them:

- a. If the train is stopped in the station
 - the train doors are opened and the passengers are disembarked from the train on the waiting platform, then on the escape routes to the safety seats;
 - the driver reports the problem to the dispatcher and acts to extinguish the fire or prevent its spread with fire extinguishers or water hoses from internal hydrants, if the voltage sources of trains and contact rails are disconnected;
 - in case the fire cannot be extinguished by these measures, the driver requests through the dispatcher the alert of the intervention team from the metro station, of the intervention, rescue and first aid team or of the professional services for emergency situations.
- b. If the train is on the move
 - if the driver notices while driving a fire or damage with smoke, toxic gases and high temperatures on the train, disconnects the traction and tries to reach the first station using the train's inertia, ordering the descent of all collectors and reporting to the dispatcher the identified problem;
 - after stopping the train at the station, it acts according to the provisions of the previous point.
- c. If the train is on the move and it suddenly stops in the tunnel
 - if the driver notices while driving a fire or damage with smoke, toxic gases and high temperatures on the train leading to uncontrolled stopping of the train in the tunnel, the driver addresses passengers using the sound system and recommends keeping calm and banning going down the tunnel on their own initiative, awaiting the intervention of Metrorex staff;
 - urgently reports the problem to the dispatcher in order to disconnect the voltage from the third rail, turn on the normal lighting in the tunnel and start the ventilation installation in evacuation mode, indicating its approximate position and the problem found;
 - in the situation when the radio connection with the dispatcher cannot be established or if the passengers' lives are endangered, the train driver disconnects the voltage from the third rail, from the train, by inserting the short circuits;
 - if the radio connection with the dispatcher has been established and the confirmation of the disconnection of the voltage from the third rail has been received, after lowering the collectors and introducing the short circuits of the whole train, the driver intervenes with the extinguishers to try to extinguish the fire;
 - if the damage can affect the integrity of the passengers, the assistance mechanic helps to disembark the passengers from the train, starting with those in the damaged frame and driving them to the nearest station, in the opposite direction to the exhaust air current, according to the regulations in force.

In annex no. 11 of the same normative act is presented the list of vital points vulnerable to fire in the subway locations, where a technological ventilation plant can also be found.

2.2 International standards

Unlike in the field of car tunnels, where regulations on fire safety are very detailed and strongly harmonized internationally, in the field of metro tunnels these issues are less treated and standardized. With regard to mechanical ventilation installations in particular, the rules may differ in the same country from project to project, sometimes being adapted to the technology available at the time of construction [14].

At European Union level, there is a European Commission decision regulating the safe construction and operation of railway tunnels [15], but this does not apply to metro tunnels, nor is there any other European regulation in this regard.

Therefore, the following subchapters will present the regulations regarding smoke extraction installations in countries that have implemented specific regulations for fire safety of subway systems.

2.2.1 Decree approving the technical regulations for fire prevention in the design, construction and operation of metropolitan railways – ITALY (2015)

The purpose of this decree [16] is to establish the rules for the construction of metropolitan railways, including subways, in terms of fire safety. They apply to new constructions or modifications to older constructions.

The primary objective of protecting people must be pursued by ensuring the survival of people in the immediate vicinity of the fire source, as well as by protecting people who use escape routes to a safe area.

The most important scenarios considered when establishing these technical regulations are:

- Scenario 1: fire on a train stopped in a subway station
- Scenario 2: fire on a train stopped in a subway tunnel
- Scenario 3: fire to a shop on the subway platform
- Scenario 4: fire in an equipment room.

The minimum thermal load for fires in scenarios 1 and 2, required for the calculation of fire parameters such as temperature, flame height and smoke flow, is 7000 kW. This value is the maximum that can be reached by that fire, which develops after a time function that describes a development of the fire power of 1000 kW in 210 seconds.

For scenarios 3 and 4, the minimum thermal load is considered to be 3500 kW, representing the maximum value that can be reached by the respective fire until the entry into operation of the automatic fire extinguishing installation.

The regulations provide for the critical values of the limit conditions to which people could be exposed in the event of a subway fire. The following limits must not be reached when designing fire prevention and protection measures:

- Exposure of people to a thermal radiation of the smoke layer higher than 2.5 kW/m²;

- Visibility of at least 15 m at a height of 1.8 m from the floor, in order to be able to observe the evacuation signs from the building;
- The average fractional effective dose of CO should not exceed 0.3.

These values must not be reached for a period of time at least twice the time required for the safe evacuation of persons.

Sustainable conditions for people that can be encountered on escape routes for an indefinite period of time are:

- Average air temperature of maximum 40° C
- Visibility of at least 30 m in terms of perception of evacuation signs
- The average fractional effective dose of CO should have a maximum value of 0.1.

Emergency ventilation systems are essential for the safety of people in subway stations, which is why they must be designed and installed in such a way as to achieve the following objectives:

- in case of a fire on a train stopped in the tunnel (scenario 2), the necessary conditions must be ensured for the evacuation of passengers through the tunnel to the nearest station or emergency exit. The air ventilation speed must be at least equal to the critical speed and not less than 2 m / s. During the evacuation of persons from the train, the limits of the sustainable conditions described above must not be exceeded;
- in case of a fire on a train stopped at the station (scenario 1) the conditions for the safe evacuation of passengers on the platform and then on the escape routes must be ensured.

Sustainability conditions must not be exceeded for at least 10 minutes from the opening of the train doors next to the platform.

The legislation stipulates that tunnels with a maximum length of 300 m do not require the installation of an emergency ventilation system or an escape route parallel to the railway line.

Emergency ventilation must ensure that fresh air is introduced in the opposite direction to the evacuation of persons.

A very important aspect is that emergency ventilation installations must be designed so as to achieve the objectives verified by CFD analysis. CFD tests of scenarios involving the activation of the ventilation system in emergency situations will be performed, in order to set design references for future field tests.

With regard to smoke extraction and emergency access wells, they must comply with the following conditions:

1. Each tunnel section longer than 300 m shall be equipped with an emergency ventilation system.
2. In general, the air intake is made through the middle of the tunnel section to facilitate the movement of evacuated persons to the nearest station and the access of firefighting personnel.
3. In the case of individual tunnels served by a single well, it must be partitioned vertically to prevent smoke recirculation between tunnels.

4. In the case of tunnel sections longer than 750 m, at least one ventilation shaft shall serve as an emergency access for firefighters.
5. Where ventilation shafts are also used as emergency access shafts, they must be constructed in such a way that the shaft used by rescuers is independent of the routes of fresh air introduction or smoke evacuation.
6. The wells referred to in the previous point must be provided with a ladder with a maximum gradient of 70° and resting places every 8 m, so that lifeguards equipped with protective equipment can access the surface tunnel.
7. The grilles of smoke or fresh air wells must prevent the accidental introduction of dangerous substances into the tunnel at ground level. and not be located on roads or in areas where the public has easy access.

The regulation also imposes conditions for the ventilation of escape routes, as follows:

1. In underground stations, the compartmentalization of the air on the escape routes shall be carried out using air curtains supplemented with ventilation systems which introduce sufficient air into the station to generate overpressure on the escape routes from the fire area.
2. Smoke curtains can be used, especially on stairs and sub-vertical paths.
3. In the case of single-room underground stations, smoke and heat extraction systems complying with the UNI 9494-2 standard may be used.
4. Air curtains located between the underground station and escape routes using local air sources are prohibited. The air source must be external, from an area located at least 25 m from the station.
5. The speed of the air introduced by the air curtains must be high enough to ensure pneumatic sealing against smoke and hot gases generated by the fire. However, the speed of the air must not hinder the passage of people or cause panic among them.
6. The air velocity of the overpressure exhaust routes must be between 1 and 6 m/s, measured in the section of the protected route closest to the platform.

The choice of fans in the smoke exhaust system will be made according to the estimated smoke temperature. Classes of fans used in smoke extraction systems must not have a fire resistance of less than F400/90 min.

The operation of the emergency ventilation systems of a metro network must be supervised from a dedicated control centre, where all information on ordinary and emergency operations is centralized.

2.2.2.1 Inter-ministerial technical instructions on safety in railway tunnels no.98 300 from 8th July 1998 - FRANCE

In France, the fire safety of metro systems is well regulated by specific legislation covering the whole spectrum of this field.

These inter-ministerial instructions [17] apply to newly built tunnels between 400 and 10,000 m in length (including metro tunnels). Here the tunnels are classified according to the types of

railways they serve, the minimum standards of resistance and reaction to fire that these types of constructions must comply with are indicated, the fire protection installations are described, as well as the escape routes in emergency situations.

As for smoke extraction installations, they are mandatory in the following cases:

- In the case of tunnels that serve the urban transport railway lines;
- Tunnels with a length of more than 5 km through which dangerous materials are transported.

The air circulation speed must not be less than 1.5 m/s, the power of the smoke installation being adapted to the most frequent local meteorological conditions.

De-smoking is provided by a group of two reversible motors powered by two different electrical sources.

Fans must withstand a temperature of at least 200⁰ C for 2 hours.

There must be a device for manually activating the smoke system in each station to facilitate the intervention of firefighters in case of fire.

2.2.2.2 Joint Order of 20 February 1983 approving the safety rules and control procedures applicable to spaces accessible to the public, located on the public railway and strictly essential for their operation (2008) - FRANCE

This Regulation [18] clarifies the mandatory conditions to be implemented for above-ground and underground stations (including metro stations).

Regarding the smoking of underground stations, the regulation stipulates that this can be done naturally or mechanically, if the station has a single underground level, and mandatory mechanically if it has several underground levels.

Natural smoke must have several connections with the outside, in addition to the openings used by passengers, with a total area at least equal to 50 per cent of the underground surface, the vents not being concentrated in the same area. In this case, the smoke extraction pipes must comply with the following conditions:

- Their section must be at least equal to the free surface of the vents they serve
- The ratio of the largest and smallest section must be less than or equal to 2
- The pipes must be made of non-combustible materials and have a fire resistance of at least 15 minutes. If they pass through spaces with a higher fire resistance, they must also respect the respective degree of fire resistance.
- Exhaust manifolds (vertical) must not have more than 2 deviations of 20⁰
- The horizontal connections of the ventilation ducts must not have a length of more than 2 m for an efficient draft (the calculation was made for a smoke temperature of 70⁰ C and an outdoor temperature of 15⁰ C, without wind).

Mechanical smoke extraction is performed on areas defined according to the construction of the underground station. For each such area the minimum refresh rate must ensure a minimum of 15 shifts per hour. In addition, each area must be equipped with an independent ventilation

assembly (suction and discharge), so that in the event of a fire a pressure is created in that area and in the adjacent areas an overpressure.

Smoke fans must operate at smoke temperatures of 400⁰ C for one hour. They must be powered by two independent electrical sources.

The smoke extraction system must be able to be activated both manually and automatically. The smoke extraction flow must be 1 m³/s for every 100 m² of ventilated area.

2.2.3 The standard of fire safety in fast transit systems – SINGAPORE (2012)

This standard [19] sets out fire protection and safety requirements for underground, surface or above-ground rapid transit systems. It provides for passive and active fire protection measures, measures for the protection of escape routes, the intervention of professional emergency services and other aspects in the field of fire safety of buildings.

The section on smoke control in mechanical ventilation stations and systems has the following main objectives:

- Maintaining safety conditions for evacuating passengers
- Smoke management in the station for carrying out extinguishing operations

Fresh air/smoke from the smoke control and mechanical ventilation system can be sucked in/out through the air intake/exhaust wells outside the station.

Fresh air/smoke wells must be positioned so as to prevent the recirculation of smoke into the system through the suction openings, station entrances or other openings at the surface.

If the replacement air is sucked in through the door openings at the entrance to the station, devices must be incorporated to allow the air to be replaced when the emergency ventilation system is activated and if the station doors are closed outside passenger opening hours.

AIR CONDITIONING AND MECHANICAL VENTILATION SYSTEMS

Where air conditioning is intended to be used in place of emergency ventilation instead of mechanical ventilation, all requirements of this standard shall apply to the air conditioning system.

The mechanical ventilation system for pressurizing stations and stairwells shall comply with the provisions of the *Code of Practice for Mechanical Ventilation and Air Conditioning in Buildings - SS553*, unless changes are provided in this standard.

- Mechanical ventilation on the fire escape must generate a positive pressure towards the adjacent rooms.
- The protective sleeves of the pipes, the lining of the pipes and the flexible connections must be made of non-combustible materials. If combustible materials need to be used, they must have a surface flame spread rate of at least class 0.
- Rooms that have no other purpose than to protect the air ventilation equipment and the related electrical devices are not considered as areas with high fire risk.
- If the air supply pipe serving the stairwell must penetrate the wall and protrude, the portion of the pipe outside the staircase must be embedded in the masonry with at least the same fire resistance as the elements of the structure and not must be fitted with fire dampers.

- Battery chambers must be ventilated to keep the average volume of hydrogen in the chamber below 2%.
- Fire dampers must not be used in the following locations:
- Openings in the walls of the ventilation shafts for the piping of the emergency ventilation system.
- Anywhere in an air pressurization system.

The elevator shaft must be ventilated in accordance with *SS 550 Code of Practice for the installation, operation and maintenance of passenger and material lifts*. Ventilation openings must be positioned so as to induce exhaust air from the well. If no openings can be made due to the positioning of the well, a ventilation duct may be installed. If the pipe is not fire resistant, flaps must be installed at the well wall.

If the lift shaft is not protected, it must be ventilated at the top through a permanent opening with an area of at least 0.1 m² for each lift.

SMOKE CONTROL SYSTEM

It is a dedicated system that must be provided in the commercial spaces in the basement and must comply with SS 553 - Code of Practice for mechanical ventilation and air conditioning in buildings.

Linear temperature detectors such as fibre optics can be used instead of smoke detectors to activate smoke control systems in non-public areas.

SMOKE FILTRATION SYSTEMS

They must be provided in the following spaces:

- i. Public space stations
- ii. Auxiliary space corridors in the basement

Except:

iii. The corridors that serve only the rooms of the toll machines, the staff offices, the toilets, the cleaning spaces and not much more than a technical room.

- iv. Corridors in buffer zones.

The smoke filtration system must meet the following requirements:

i. At least 2 sets of smoke filter fans must be provided. Each of them must be able to ventilate at least 50% of the projected air flow.

ii. The air speed at the doors and aisles must not exceed 5 m / s.

iii. The smoke extraction openings must be distributed in such a way that no uncovered area remains.

iv. The pipes of these installations passing through other upper-class fire compartments must be so constructed as to comply with the requirements of that class.

v. The suction and discharge fans must be interconnected so that shutting down / malfunctioning the discharge fan automatically leads to the shutdown of the appropriate intake fan.

vi. The smoke filtration rate must be at least 9 shifts per hour.

vii. The air filtration system must be activated automatically by the fire alarm system. In addition, a manual switch must be fitted to enable the system to be activated from the control centre or from a control panel installed on the first floor.

viii. Horizontal pipes must be made of 1.2 mm thick steel.

ix. The extraction fan must be able to operate in normal parameters at 2500 C for 2 hours and have an alternative power supply.

The smoke filtration system does not have to be a dedicated one. If flaps are used to direct the smoke to the filtration system, they must be equipped with a motor.

Stores must not be equipped with a smoke control system.

Public spaces outside commercial premises must be equipped with a smoke filtration system.

The smoke filtration system in the public space of the station must be activated automatically by detectors located in the public spaces of the station.

UNDERGROUND AND CLOSED EMERGENCY VENTILATION SYSTEM

The emergency ventilation system of underground stations must be constructed in such a way as to meet the following conditions:

- To ensure safety conditions on the escape route from the place of fire to the safety zone
- Be able to reach operational parameters in no more than 120 seconds.
- The emergency ventilation system must be designed so that if one fan fails the others will be able to take over its functions.
- The maximum speed of the fresh air blown in the opposite direction of the exhaust direction must not exceed 5 m / s.

The design of the emergency ventilation system must take into account the following parameters:

- Specific heat release rate of train sets and combustible materials they can carry
- Fire development rate
- Geometry of stations and tunnels
- Fans, ducts, wells and devices used for air circulation
- Operational procedures for action in case of fire to ensure a prompt and efficient response.

Fans that have not been designed to operate in the event of a fire must be switched off automatically when the emergency ventilation system is activated, unless it can be shown that it does not affect the emergency ventilation air circuit in any way.

Emergency fans, motors and other components exposed to the air flow must be operated at temperatures of 250° C for at least 2 hours.

Emergency fan motors must reach the intended operating speed within a maximum of 30 seconds of the off position, or a maximum of 60 seconds for variable speed motors.

Devices for manually activating emergency fans must be located as far away as possible from the air flow generated by them. It is forbidden to mount thermal overload protection devices on emergency fan motors.

Activation of the emergency ventilation system must be done from the Operations Command Centre. The operation of the fans in the Passenger Services Centre (local) can be done only with the consent of the operators in the Operations Command Centre.

If the fresh air flow is ensured by air intake fans or access routes, devices for their automatic opening must be installed once the emergency ventilation system has been activated.

2.2.4 Fire safety standard for fixed transit systems and passenger rail systems, NFPA 130 – USA (2010)

This standard [20] includes fire safety measures in terms of underground, surface and above-ground fixed transit systems, referring, but not limited to, to stations, taxiways, tunnels, systems. emergency ventilation, trains, emergency procedures, communications, control systems and train parking areas.

As regards the emergency ventilation system, it is expected that it will be installed under the following conditions:

- In a closed system station
- In an underground system or tunnel with a length greater than 305 m (1000 ft)

The mechanical emergency ventilation system must not be installed under the following conditions:

- In an open system station
- If the length of the tunnel is less than or equal to 61 m (200 ft)

If, following an engineering analysis, it is found that mechanical ventilation can be replaced by natural ventilation, this may be done under the following conditions:

- If the length of the tunnel is greater than 61 m and less than 305 m
- In a closed station where the engineering analysis demonstrates that by using natural ventilation the same safety criteria of the users are observed.

The engineering analysis of the ventilation system must include a validated program of analytical simulation of the subway, accompanied by a quantitative analysis of the dynamic air flow generated by the fire scenario, as would result from the application of the CFD technique. The result of the analysis must include the in-situ measurement of cold air velocities (in the absence of fire), during the commissioning of the installation.

The emergency ventilation system must be able to perform the following:

- To ensure a safe climate on escape routes in closed stations and tunnels
- Ensure air ventilation at a speed at least equal to the critical speed in tunnels
- To be fully operational in no more than 180 s
- To maintain the necessary air flows for at least 1 hour but not less than the time required to create safety conditions.

Smoke ventilation systems with extraction wells are permitted only if the engineering analysis shows that the spread of smoke in the tunnel is limited to a maximum of 150 m.

The analysis must take into account at least the following possible events:

- Fire in tunnel or subway station
- Local incident in the electrical room that leads to the interruption of the power supply of the emergency ventilation system
- Derailment

With regard to fans used in emergency situations, they must be able to ventilate the air in both directions, as required.

The motors of the individual fans must reach the operating speed in maximum 30 s, and in the case of motors with variable speed in 60 s.

The emergency ventilation system must be able to be switched off and the flaps closed so as to limit the dispersion of toxic gases, if necessary.

Fans, their motors and all ancillary components exposed to smoke must operate at ambient temperatures of 250⁰ C for at least 1 hour but not less than the time required to ensure safety.

This temperature can be reduced following an engineering analysis, but not less than 150⁰C.

The starter of the local fan motors and their operating and control devices must be positioned as far as possible from the ventilated air flow.

It is not permitted to install emergency fan overheat protection devices.

Fans that are used only for the comfort of passengers or workers and that are not intended to be part of the emergency ventilation system must be switched off automatically when a fire is identified so as not to affect the air currents generated by the fans. emergency.

The operation of the entire emergency ventilation system must be initiated from the operations control centre (dispatcher) of the metro network.

Local control of the ventilation system over the remote control of the control centre must be permitted.

The operation of the emergency ventilation system must only be interrupted by order of the intervention commander.

Annex B of this standard provides more details on ventilation and safety limits for exposure to the effects and consequences of fire.

Exposure to heat can endanger people's lives in 3 ways

- Hyperthermia
- Burns on the skin
- Burns of the respiratory tract.

If the humidity in the air is less than 10%, burns to the respiratory tract occur after burns to the skin. However, airway burns may occur after inhalation of air above 60⁰ C if saturated with water.

The safety limit for radiation exposure is approximately 2.5 kW / m². Below this level of radiative flux the exposure can be tolerated for 30 minutes or more without visibly affecting the discharge. Above this value, the time of occurrence of skin burns decreases rapidly according to the relation:

$$t_{\text{rad}} = 4 \cdot q^{-1.35}$$

where,

t_{rad} = time [min]

q = radiative heat flux [kW/m²]

As with toxic gases, an exposed person is thought to accumulate a dose of radiant heat over a period of time. The equivalent fractional dose (EDF) of radiant heat accumulated per minute is the inverse of t_{rad} .

The convective heat accumulated per minute depends very much on the degree of coverage of the skin with clothes and the nature of those clothes. For fully clothed persons, the following formula for determining the time of onset of burns may be used:

$$t_{\text{conv}} = (4.1 \cdot 10^8) \cdot T^{-3.61}$$

and in the case of more modestly dressed persons, the following formula is more recommended:

$$t_{\text{conv}} = (5 \cdot 10^7) \cdot T^{-3.4}$$

where,

t_{conv} = time [min]

T = temperature [°C]

These equations have been determined empirically and are estimated to have an uncertainty of $\pm 25\%$.

Thermal tolerance data for uncovered skin indicate a limit of 120° C for convective heat, the value above which appears, in a few minutes, considerable pain and the appearance of burns.

The body of a person exposed to a heat source can be considered as taking over a dose of heat over a period of time. A short exposure to a high power radiant flux is less tolerable than a longer exposure to a lower power radiant flux. For the calculation of this dose the methodology from the calculation of the fractional dose of toxic gases may be used, using the following formula:

$$\text{FED} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{\text{rad}}} + \frac{1}{t_{\text{conv}}} \right) \cdot \Delta t$$

The time for which the FED has a value greater than 0.3 is the time available for evacuation in the event of exposure to convective and radiant heat.

Tab. 1 Maximum exposure time

Exposure temperature (° C)	No incapacity generated (min)
80	3,8
75	4,7

70	6,0
65	7,7
60	10,1
55	13,6
50	18,8
45	26,9
40	40,2

CO content:

- Approximately 1150 ppm or less for the first 6 minutes of exposure
- Approximately 450 ppm or less for the first 15 minutes of exposure
- Approximately 225 ppm or less for the first 30 minutes of exposure
- Approximately 50 ppm or less for the rest of the exposure period.

Smoke dimming levels must be kept permanently below the point where 80 lx light signals are visible from 30 m and doors and windows are visible from 10 m.

The air speed in closed stations and tunnels must be at least equal to 0.75 m / s.

The speed of air in closed stations and tunnels used for emergency evacuation must not exceed 11 m / s.

The maximum noise level should be 115 dB for a few seconds and 92 dB for the rest of the exposure.

Ventilation systems under the platform are recommended for extracting heat generated by traction and braking devices. Ventilation vents should be made below the platform level, near heat generating devices.

The installation of safety doors (platform screen doors / edge screen doors) is an effective option to ensure comfort in the station and smoke control in tunnels. They must meet conditions of fire resistance and structural strength close to those of the train.

In the case of a scenario involving evacuation from the tunnel to the station, the access of persons from the tunnel to the platform must be taken into account.

2.2.5 Technical standard for Japanese railways (2012)

By *Order of the Minister of Land, Infrastructure, Transport and Tourism no. 51/2001* [21] technical rules have been implemented to ensure the stability and safety of public rail transport, including the metro system.

With regard to emergency ventilation, Article 29: Underground station facilities shall provide that underground stations and tunnels leading to them shall be equipped with mechanical fans only if they do not have access to sufficient natural ventilation.

The ventilation system (natural, mechanical or mixed) must be able to ensure the extraction of smoke so that passengers can be evacuated safely. If a mechanical ventilation system is needed, the station will be equipped with a backup electric generator.

In the metro stations, smoke barriers between the platform and the tunnel may be installed, if deemed necessary, at stairs, elevator shafts or other locations where the spread of smoke must be limited. They can be activated by a smoke detector or an operator in the disaster prevention and control centre and must be made of a fire-retardant material.

It should be noted that the English version of the document was not translated very well, which is why some paragraphs were more difficult to understand. It is also possible that the Japanese translation is incomplete, as it is not an official translation.

The determination of the smoke evacuation capacity at the level of the waiting platform or the lobby is made on the basis of the fire scenarios on trains or in the metro stations, presented in the table below:

Tab. 2 Fire scenarios

Type of fire	Fire location	Fire source
Small fire	Train	Mechanical equipment of the train
	Platform	Burner using a small ignition source
Major fire	Train	Burner using gasoline
	Platform	Burner using gasoline

A. Minor fire verification procedure

A.1 Checking the smoke density at the platform level

In the case of ordinary platform fires, the smoke density C_s , calculated according to the volume of smoke diffusion and the minimum time to discharge, must have a value of less than 0.1 (1/m).

To estimate the smoke density the following empirically determined formulas are used, depending on the fire scenario considered:

(1) Train fire

- a. If the evac time is less than 7 minutes

$$C_s = 21 \cdot (1 - e^{-V_e \cdot t / V}) / V_e$$

- b. If the evac time is bigger than 7 minutes

$$C_s = (66 \cdot V \cdot e^{-V_e \cdot \frac{t-7}{V}} - 21 \cdot V_e \cdot e^{-V_e \cdot \frac{t}{V}} + 66 \cdot V_e \cdot t - 441 \cdot V_e - 66V) / V_e^2$$

(2) Shop fire on the platform

- a. If the evac time is less than 10 minutes

$$C_s = 2,1 \cdot (V_e \cdot t - V + V \cdot e^{-V_e \cdot t / V}) / V_e^2$$

- b. If the evac time is between 10 and 11 minutes

$$C_s = \{(24 \cdot V - 21 \cdot V_e) \cdot e^{V_e \cdot (t-10)/V} + 24 \cdot V_e \cdot t - 198 \cdot V_e - 26,1 \cdot V + 2,1 \cdot V \cdot e^{-10 \cdot V_e/V}\} / V_e^2$$

c. If the evac time is bigger than 11 minutes

$$C_s = \{(1,8 \cdot V - 45 \cdot V_e) \cdot e^{-V_e \cdot (t-11)/V} + 1,8 \cdot V_e \cdot t + 91,2 \cdot V_e - 27,9 \cdot V + 2,1 \cdot V \cdot e^{-10 \cdot V_e/V} + (24 \cdot V - 21 \cdot V_e) \cdot e^{-V_e/V}\} / V_e^2$$

where,

C_s = smoke density or extinction coefficient (1/m)

V = volume of smoke block [m^3]

t = evac time [min]

V_e = smoke evacuation flow rate relative to the volume of the smoke block [m^3/min]

If there is no shop on the platform, $t=0$, so $C_s=0$.

(3) Volume of the smoke block

The volume of the smoke block is the space where the smoke density is estimated to be the highest of the total platform flooded with smoke during the fire.

The volume of the smoke block is determined using the following formulas:

$$V = (A_0 - A_v) \cdot 20$$

$$A_0 = (V_a - V_m) / L$$

where,

A_0 = area of the section filled with smoke [m^2]

A_v = area of train section [m^2]

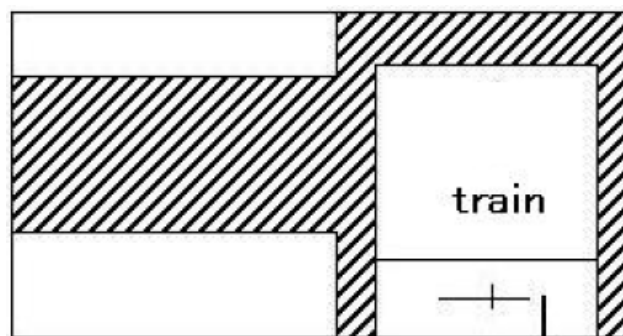
V_a = the total volume calculated from the smoke block section and the length of the platform [m^3]

V_m = volume of parts with no smoke from V_a , like pillars, stairs etc. [m^3]

L = platform length [m]

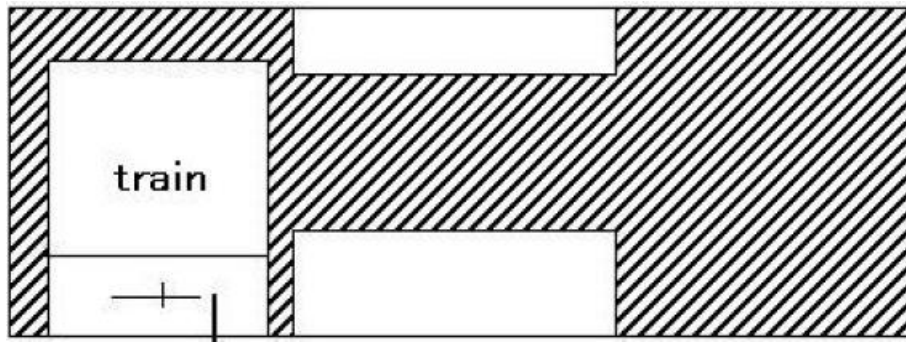
The following figures show examples of calculating the area of the smoke-flooded section:

Fig. 1 Platform with one metro tunnel



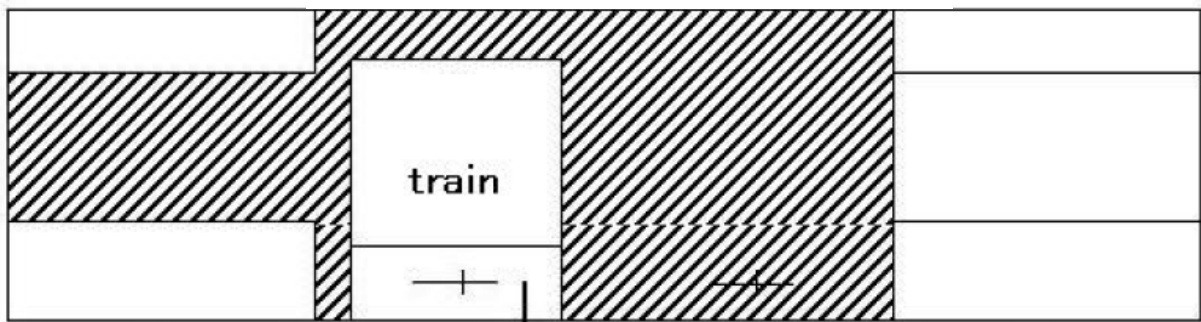
In this case we assume that the smoke will spread throughout the hatched section.

Fig. 2 Island platform with double tunnel



In this case the smoke will spread both on the platform and in the parallel tunnel, if no physical barriers are installed (e.g. security doors – *platform screen doors*)

Fig. 3 Opposite platforms with two tunnels



In this case it is very likely that the smoke will not spread on the opposite platform because the ceiling of the platform is lower than that of the tunnel.

(4) Minimum smoke extraction rate

The platform-level smoke extraction system should have a minimum flow rate of 5000 m³/h for the volume of the smoke block.

A.2 Checking the volume of smoke diffusion required for other different levels of the platform

The required volume of smoke diffusion (V_0) corresponding to the exhaust time t must be calculated using the formulas below and rounding to one decimal place. The volume of smoke diffusion (V) calculated separately should not be less than the required volume of smoke diffusion (V_0).

- a. If the evac time is less than 10 minutes

$$V_0 = 10,5 t^2$$

- b. If the evac time is between 10 and 11 minutes

$$V_0 = 120t^2 - 2190t + 10950$$

- c. If the evac time is bigger than 11 minutes

$$V_0 = 9t^2 + 252t - 2481$$

Smoke diffusion volume (V) is determined using the following formulae:

$$V = V' + t \cdot V_e'$$

$$V' = (A_f - A_t) \cdot (H - 2)$$

$$V_e' = V_e \cdot (H - 2) / H$$

where,

V' = smoke diffusion volume without taking into account the exhaust flow of the smoke exhaust system [m^3]

V_e' = extraction flow [m^3/min]

A_f = area of the lobby [m^2]

A_t = the lobby area covered by other objects (pillars) [m^2]

H = lobby height [m]

V_e = the smoke extraction flow of the installation from the lobby level [m^3/min]

B. Major fire verification procedure

The time required for the smoke level limit to fall to the limit of 2 m from the floor (t_0) can be calculated using the formulas below, and it must be confirmed that the calculated time required is greater than the time required for evacuation (t), calculated separately.

(1) In the event of a train or shop fire on the platform

$$t_0 = V_E / (V_s - V_e')$$

$$V_E = (A_E - A_v') \cdot L$$

$$V_e' = V_e \cdot (A_E - A_v') / (A_0 - A_v)$$

where,

$(V_E - V_e')$ is zero or has a negative value, $t_0 = \infty$

V_E = volume of the hole platform, at 2 m above the floor (m^3)

V_s = smoke flow and generation rate, both with a value of 300 (m^3/min)

V_e' = the effective smoke extraction rate relative to the actual volume (V_E) of the whole platform (m^3/min)

A_E = the area of the platform section positioned at right angles to the railway, 2 m from the floor, excluding pillars, stairs etc. (where the smoke does not spread) (m^2)

A_v' = the area of the train section 2 m above the platform (m^2)

V_e = the smoke extraction flow of the installation on the platform (m^3/min)

A_0 = section area positioned at right angles to the railway used in calculating the volume of the smoke block (m^2)

A_V = the area of the train section (m^2)

(2) In the case of lobby fires (unless the lobby is separated independently into two or more parts)

$$t_0 = V' / (V - V_e')$$

$$V' = (A_f - A_t) \cdot (H - 2)$$

$$V_e' = V_e \cdot (H - 2) / H$$

where,

$(V' - V_e')$ has the value 0 or is a negative number, $t_0 = \infty$, and in the case of the lobby without a store, if t_0 is greater than or equal to 3, $t_0 = \infty$,

V' = smoke diffusion volume without taking into account the extraction flow of the smoke ventilation system (m^3)

V_s = smoke generation rate = $300 m^3/min$

V_e' = effective extraction flow (m^3/min)

A_f = the surface area of the lobby (m^2)

A_t = the area of the pillars, stairs etc. from the lobby level, where the smoke cannot spread (m^2)

H = the height of the lobby ceiling (m)

V_e = the extraction flow of the smoke ventilation installation from the lobby level (m^3/min)

C. Counter measures

If the capacity of the mechanical smoke extraction system is not large enough, the following measures are recommended:

- Creating additional escape routes or widening the existing ones, in order to reduce the time required to carry out the evacuation;
- Increasing the volume of smoke diffusion;
- Construction of stores made of fire-resistant materials and provision of sprinkler installation;
- Avoiding building shops in subway stations;
- Provision of additional measures for the safe evacuation of persons.

Tab. 3 Comparison between the norms presented above

	Ventilation of evac routes	Evac of people against the ventilation flow	Time to change the direction flow of the fans	Max temp for the functioning of the fan [°C]	Minimum functioning period of the fan	Max radiative flux from the smoke [kW/m ²]	Minimum visibility	CO maximum concentration
România	Using over- pressure	X	max 3 min	200 - 400	period equal to intervention time	-	10% up to 2 m above the floor	-
Italy	Using over- pressure	X	-	400	90 min	2,5 kW/m ²	min 15 m at 1,8 m above the floor	effective fractionary dose max 0,3
France	Using over- pressure	-	-	200 in tunnel 400 in station	2 h in tunnel 1 h in station	-	-	-
Singapore	-	-	-	250	2 h	-	-	-
USA	-	-	-	250	1 h	2,5 kW/m ²	10 m to doors 30 m to light signals	between 50- 2000 ppm

	Viteza de ventilare aer în tunel [m/s]	Viteza de ventilare aer pe căi de evacuare [m/s]	Lungime minimă tunel	Verificare CFD	Nr de schimburi orare de aer	Timp de intrare în regim de funcționare
România	-	-	-	-	-	-
Italy	min 2	1-6 m/s	300 m	X	-	-
France	min 1,5	-	400 m	-	15	-
Singapore	-	max 5 m/s	-	-	9	max 120s
USA	-	max 11 m/s	305 m	X	-	max 180 s

Tab. 3 it is not exhaustive, the previously presented norms containing much more information and regulations than those mentioned in the head of the table, but some aspects considered essential in ensuring the fire safety of tunnels and metro stations were chosen for comparison.

The technical instructions and regulations do not follow the same structure in each country, making it very difficult to synthesize the information contained and compare them. They are adapted to their own legislative framework and their provisions differ greatly depending on the year in which the last update was made.

Regarding the regulation of platform screen doors, the only norm that refers to them is NFPA 130 from the USA, mentioning that they represent an effective option for ensuring comfort in the station and smoke control in tunnels, if the structural strength and resistance to fire are close to those of the subway liner. It is mentioned, however, that attention must be paid to the access of people from the tunnel on the platform in case of a fire that involves evacuation from the tunnel to the station and prepared measures in this regard.

Regarding the safety conditions of people who self-evacuate in an emergency situation, the regulations in the USA and Italy present maximum values of the heat radiated by the smoke layer, of the visibility and of the CO concentration that must be maintained by the operation of the installations of smoke.

The only two aspects present in the 5 regulations in the table refer to the maximum smoke temperature for which the fans (and their assemblies) must work (200 - 400°C), as well as the mandatory minimum operating time (1 -2 hours).

3. Documentary study on efficient ventilation solutions in emergency situations in metro stations and tunnels

To determine effective ventilation solutions in emergency situations, the researchers focus on determining the values of parameters specific to the development of fire in tunnels, such as critical ventilation speed, backlayering distance, flame length, maximum smoke layer temperature and toxic gas concentration.

The critical speed is the longitudinal ventilation speed required to prevent the movement of the smoke layer against the ventilation direction, and the backlayering distance is the length travelled by the smoke layer in the counter current of the longitudinal ventilation. In other words, in order to reduce the backlayering distance to zero, the longitudinal ventilation speed in the tunnel had to be at least equal to the critical speed.

3.1 Studied articles

A laborious analysis of small-scale experimental studies and theoretical analysis on these parameters was performed by Haddad et al. [22], but this makes no reference to numerical studies in the field.

Hu et al. [23] performed four full-scale experiments in a car tunnel and compared the measured values of the fire parameters with the results of CFD simulations, concluding that the values obtained from numerical simulations for smoke layer temperature, critical speed and backlayering distance are very close to the experimental results, with a deviation of only 40 °C for the predicted temperature at a distance of more than 80 meters from the fire source.

David Purser used numerical simulation to determine the conditions inside the Mont Blanc tunnel during the 1999 fire [24]. The initial conditions used for the simulation were taken from real-scale experiments conducted a few years ago in the same tunnel. The numerical results were then used to estimate the time period until the conditions in the tunnel became dangerous for passengers. An analysis of the fractional effective dose was then performed to determine the time required for the damage and subsequent death of the passengers in relation to their position in the tunnel. The fractional effective dose of a pollutant or irritant is the limit of concentration or dose that causes adverse effects in humans. This dose is calculated taking into account the time of exposure required for loss of consciousness or death of humans and the actual time of exposure to that pollutant / irritant [25]. The conclusions of the study validated the results obtained numerically, confirming once again the usefulness of CFD analysis in describing the evolution of fires in the tunnel.

Guo et al. [26] studied the impact of tunnel geometry (single-line tunnel or two-line tunnel) on the efficiency of the ventilation system in emergency situations. Given that the studied tunnel passes under a river, approximately half of the length of the tunnel is built on a positive slope, the other half being built on a negative slope, with maximum values of (+) or (-) 28 %. Because real-scale experiments could not be performed, the research was based on Froude modelling and CFD simulation, with both methods tracking carbon dioxide concentration

fields, ambient temperature, smoke and visibility. The two methods generated very close results, the conclusion being that the best conditions for the safe evacuation of passengers in case of a tunnel fire are ensured by the configuration with the double tunnel (with two subway lines).

Researchers Altan and Sumen [27] conducted a CFD study focused on the effect of tunnel blockages on the critical speed of ventilated air and temperature distribution. In this regard, they considered 3 different cases, the first with a fire source in the tunnel and without a locking element, the second with a locking element upstream of the fire source and the last case with the locking element downstream of fire source. The critical speed in the first scenario was 0.67 m/s, a value confirmed in previous studies, and the speeds obtained for the other two scenarios were 0.77 and 0.75 m/s. The authors concluded that the parameters of the fire in the tunnel are influenced by the shape, size and position of the locking element.

Teodosiu et al. [28] studied the efficiency of the two-station ventilation system and a ventilation gap in the middle of the tunnel. The scenario studied in the article involved a fire in a train stopped in the tunnel, 250 m from a station and 750 m from the station in the opposite direction, requiring emergency evacuation of passengers to the nearest station. The study was performed numerically, and for the simulation of the fire source, CO₂ and heat sources were introduced in the simulation. Results were obtained regarding tunnel air velocity, temperature fields and CO₂ concentrations. They showed that the studied ventilation strategy ensures the safe evacuation of passengers, because access to the nearest station is not restricted by air speed (not exceeding 5-6 m/s), excessive temperatures or dangerous concentrations of CO₂.

Most small-scale experiments and simulations start from the premise that the ambient pressure is normal, but in the case of tunnels built at high altitudes (3,700 m) the way in which the low pressure influences the variation of temperature and temperature should be taken into account. CO concentration. Tang et al. [29] performed a comparative numerical study between two tunnels identical in geometry located one at normal altitude and pressure (1 atm) and the other at a higher altitude (0.64 atm). The authors started from the hypothesis of a fire with a heat release rate (HRR) of 4 MW and concluded that the CO concentration profile is independent of pressure, while the temperature drop is more pronounced under pressure conditions. from which it follows that the difference between the rate of decrease of the CO concentration and the temperature is more accentuated in the case of the reduced pressure.

Weng et al. [30] studied the critical speed and backlayering length of smoke in a tunnel through a 1/10 scale experiment and CFD simulations using Fire Dynamics Simulator. The FDS simulations targeted two HRR rate values (5 and 7.5 kW), 9 different tunnel configurations (different heights and widths, even different shapes), as well as variations in the speed of the longitudinally ventilated air in the tunnel. The parameters determined in the simulations and experiments were transformed into dimensionless quantities, which were then compared, resulting in a very similar similarity between the results obtained on the two paths, a

conclusion that validates the CFD model. The authors went further and used two analytical formulas to calculate the critical velocity and backlayering length of the smoke, whose dimensionless results were smaller than the values obtained experimentally and by the CFD method, most likely due to the fact that analytical models do not take into account the loss of heat from the flame by radiation and convection.

An article studying the effect of natural ventilation on the spread of smoke in the tunnel and the temperature dependence of the smoke layer on the size of natural ventilation ducts was written by Harish et al. [31]. In this sense, several numerical simulations were performed to study different configurations regarding the location of the fire source, the number and size of ventilation ducts, etc. In the most favourable case, of the fire source just below the vent, the temperature and concentration of toxic gases decreases greatly and considerably delays the spread of smoke to the entrance / exit of the tunnel, where it could endanger the safety of self-evacuating people. If the fire is moved to the side of the tunnel, a single vent is not sufficient to completely evacuate the combustion gases, requiring the presence of several vents. The temperature of the smoke in the tunnel decreases as the surface of the ventilation duct increases, as does the amount of smoke that is ventilated through the exit / entrance to the tunnel. The article does not include an experimental part, but the results of the study were compared with the experiments presented in the literature and are very close.

The critical ventilation speed and the backlayering length of the smoke were also studied by Zhang S. et al. [32] using the numerical method. After detailing the construction of the tunnel model, it was validated by running simulations that meet the conditions of a scale experiment presented in the literature. The results obtained numerically being very close to those in the experiment, it results that the proposed model can be used to determine the critical speed and backlayering distance proposed by the authors.

The simulations covered two cases: when the backlayering length of the smoke is shorter than the train and when it is longer. From the dimensionless analysis were deduced formulas that correlate the air speed above the subway train, the fire power and the train length with the backlayering length. If the backlayering length is longer than the train, the virtual focus located on the opposite side of the train (towards the direction from which fresh air is ventilated) has been proposed as a calculation model, thus becoming the “generator” of smoke exceeding the train length. A way to calculate the power of this virtual focus by dimensionless analysis was also proposed.

A fire in the tunnel can influence the operation and efficiency of emergency fans, which is why Kazemipour et al. [33] studied this issue in a two-part study. In the first part of the study, fans are considered to be installed at the entrance to the tunnel and different power fires (HRR) are simulated to study how the power of the fire influences the pressure generated by the fans and the speed of the air. The conclusion of the simulations performed is that the speed of the air in the tunnel is inversely proportional to the power of the fire, reaching the moment when it is observed that the smoke rises towards the fans and exits the tunnel through the part where the air is ventilated (backlayering). The graph resulting from the

simulations shows a linear dependence between the speed of air circulation through the tunnel and the power of the fire.

The next series of experiments focused on the effect of the position of the fire seat on the speed of air circulation, highlighting that the proximity of the fire seat to the vent decreases the speed and pressure of the air due to the fact that smoke is entrained to the opposite outlet a greater distance and reduces air circulation speed.

The second part of the numerical study looked at the effect of fire on a fan mounted inside the tunnel, at different distances from the fire, upstream and downstream. At the first test, at a distance of 75 m upstream, the efficiency of the fan was not affected, it operating in normal parameters. If the fan is only 10 m upstream of the fire, its efficiency has decreased considerably due to the fact that the kinetic energy of the ventilated air is dissipated mainly by rubbing against the tunnel ceiling, because the dense layer of smoke directs a large part of ventilated air to the ceiling. Another cause of decreased fan efficiency is the interruption of smoke stratification and the creation of a smoke recirculation loop between the fire and the fan. The fan mounted 30 meters downstream of the fire is the most inefficient due to the fact that it absorbs a lot of smoke, with a considerably higher density than air, thus operating at much lower parameters than expected. An improvement in the performance of this fan was observed with its installation at a greater distance from the ceiling, 35 cm below, where the smoke density is lower.

The numerical procedure used previously was further used to compare the results with a full-scale experiment, in an 850 m long tunnel, the results showing discrepancies between 5 and 15% between simulation and experiment.[28]

Zhang S. et al. [34] studied the dependence between the degree of curvature of a tunnel and the critical velocity of the longitudinally ventilated air. Using the method of theoretical analysis, the authors determined calculation formulas for the backlayering length of the smoke and for the critical speed. These calculations are based on the premise that the smoke ceases to advance against the longitudinal air stream when the static smoke pressure is equal to the hydraulic pressure of the air stream. Based on the theoretically determined relations, the two variables can be calculated depending on the dimensions of the tunnel and its radius of curvature, so that the results can be compared with those determined numerically.

Regarding the numerical simulation, two tests were performed to validate the numerical model by reproducing the conditions of two experiments of Li and Hu regarding the critical speed, the results of the simulations being very close to those of the experiments. Numerical simulations aimed at changing the radius of curvature of the tunnel and the heat release rate fire (HRR) to observe how the length of the backlayering layer varies and the critical speed. Thus, from the graph recorded by the thermocouples introduced in the simulation, the backlayering length can be estimated as the distance from the maximum temperature (just above the fire) to the first sudden drop in temperature (temperature jump) to the direction from which air is introduced. From previous studies (on straight tunnels) it is known that the

backlayering distance decreases with increasing air speed and reducing the power of the fire. On the other hand, these simulations show that the backlayering distance increases with the radius of curvature of the tunnel, being maximum when the radius tends to infinity (straight tunnel). One explanation would be that the advance of smoke is hampered by a change in the direction of the ventilated air, which generates additional turbulence. The impact factor of the resistance, noted in the study with K_f , decreases with increasing radius of curvature and increases with increasing speed of air ventilation.

The article published by Wang F. and Wang M. [35] studies the impact of the location of the fire source in the tunnel section, through analytical calculation methods and numerical simulation. The tunnel model built in Fluent has a length of 300 m, with two directions of travel and fans mounted under the ceiling. In order to simplify the numerical model and reduce the calculation time, the radiative heat transfer equations are not included, which is why it is considered a 35% reduction in the value of the fire source power, a simplification approach and validated by other researchers in previous studies (Vega et al. [36]) When the fire is positioned between the two directions of travel, the critical speed of the longitudinal ventilation system is determined by numerical analysis at 2.5 m / s. The same critical speed is valid when the fire is located on one of the two directions of travel. But when the fire is close to one of the side walls of the tunnel, the value of the critical speed increases to 2.8 m / s. These values are compared with the values obtained by other researchers through theoretical analysis and the values are close to each other. The maximum temperatures of the smoke layer turn out to be 1900° C in the case of the fire located between the directions of travel, 2100° C for the fire located on one of the directions of travel and 2600° C in the case of the fire close to the wall. As for the distance travelled by the smoke in the opposite direction to the air ventilation, it is the largest in the case of the fire located in the middle of the tunnel and is reduced by half in the case of the fire located in one direction, for the same speeds of 2,4 and 2,3 m / s. In the case of the fire close to the side wall of the tunnel, the distance travelled by the smoke in the opposite direction to the ventilation is much shorter because the smoke gives off some of the heat to the wall and thus loses its inertia force needed to move against the current.

An article studying the effect of natural ventilation shafts on the attenuation of the piston effect induced by the movement of the train through the subway tunnel is the one published by Gonzales et al. [37]. Thus, the cases in which a single train moves in the tunnel or when two trains running in opposite directions move simultaneously through the tunnel are studied. The study is based on simulations in Fluent and comparisons with one-dimensional software for simulating the pressure and speed of air circulation through tunnels. The studied configuration consists of two waiting stations (platforms) of 100 m each, connected by a double tunnel of 500 m. In each station is installed a ventilation plant that introduces air into the station and tunnel (120,000 m³ / h), and in the middle of the tunnel is a ventilation duct with a boiler that mechanically evacuates the air. Also, at both ends of the tunnel, near the waiting stations, are built natural ventilation shafts, which communicate with the surface.

The scenarios studied in the article include the mechanical introduction of air into stations and the operation at different capacities of the air extraction plant in the middle of the tunnel (under the conditions of operation at normal capacity of 120,000 m³/h of the air supply plants in the two stations). These scenarios are studied both with a train that travels the distance between stations and with two trains that move simultaneously. The discretization network used is dynamic, in order to be able to simulate the piston effect induced by the train. The air velocity fields and the air pressure distribution through the tunnel and through a natural ventilation shaft near a station were analysed. The study concluded that the amplitude of the piston effect, in the studied configuration, is influenced by the central mechanical extraction. The instantaneous air flow generated by the piston effect can reach 50% of the total flow of the ventilation system, depending on the mechanical exhaust scheme used. In order to make the most of the pressure fluctuations induced by the train movement, the ventilation system should be used in such a way that the air movements induced by the train are accentuated by mechanical ventilation. This would require ventilation depending on the position of the train and its direction of movement. The natural ventilation shafts in the middle of the tunnel are very efficient in exchanging air with the outside, especially in the case of stations that are not equipped with PSD. They also have the advantage of reducing the traction required to move the train. It has been estimated that 3% of the energy needed to move the train can be saved if these natural ventilation shafts are built. Given that the piston effect is more pronounced in the case of single tunnels than in double tunnels, the efficiency of natural ventilation shafts is also higher in the case of single tunnels. The effect of natural ventilation shafts is also felt when it comes to the comfort of passengers in waiting stations, where air turbulence fluctuations generated by the approach of the train were measured and it was found that they do not exceed 4-5%, without thus compromising the comfort of the people on the waiting platform.

Like the previous article, the one published by Huang et al. [38] is based on the CFD study method with dynamic discretization network, which allows it to pay special attention to the piston effect of the subway train on the movement of air through ventilation ducts (organized natural ventilation).

Two variants of the ventilation piping are considered, namely with 3 ventilation tubes mounted individually on the two tunnels, or 3 common pipes for the two tunnels (directions of travel). Also, two variants are considered in terms of the separation of tunnels: with gaps in the wall every 200 m or with missing wall on a certain portion at the same interval. It should be noted that the dividing wall of the two directions of travel is uninterrupted in front of the vents.

The conclusions of the study state that the highest air flow is conveyed in the case of separate wall tunnels with a wall broken at an interval of 200 m and with individual pipes, then in the case of tunnels with gaps in the partition wall and individual pipes, the lowest flow being registered in the case of common piping and with gaps made in the partition wall, between the two directions of travel.

In the case of simulations with a dividing wall and gaps between the directions, the air flow on the other direction of travel is less affected by the air flow in the tunnel in which the train runs, resulting in an increase in air velocity through the pipes corresponding to the train tunnel and an increase of the piston effect.

Guo and Zhang [39] conducted a comparative study between the results of empirical formulas, experiments and numerical simulations performed in FDS and Fluent to determine the critical value of longitudinal ventilation in a tunnel. Their attention was directed to two types of tunnels, narrower or wider than 0.25 m. Their study shows that in the case of narrow tunnels, with a width of 0.25 m, FDS deviated from the predictions of other methods of speed determination. critical, calculating much higher values. This aspect is irrelevant if we consider that no subway tunnel could have this width. Regarding the experiments and simulations performed on tunnels of normal size, the results were very close, demonstrating the validity of CFD methods for calculating fire parameters, as well as the analytical calculation formula proposed by researchers.

Xi and Hu [40] studied the effect of airflow on the development of the fire of a train traveling through a tunnel. Given that the emergency procedures of some countries provide that in the event of a fire the train should move to the nearest station, it is important to study what is the optimal speed of movement so that the fire evolves as little as possible. The study was performed on a 1/8 scale model and numerical simulation in STAR CCM +. According to the experimental results, the optimal speed of the train, at which HRR, temperature and CO concentration are minimal, is about 42 km / h, corresponding to a piston effect of 19 km / h. According to the simulations performed in STAR CCM +, in which several variations of the parameters could be easily tested (train travel speed, HRR), the optimal speed is 45 km / h, thus presenting a variation of only 4% compared to the experimental results.

The article by Wu et al. [41] is based on numerical simulation in FDS and studies a 2-level subway station configuration, consisting of lobby and waiting platform. The mechanical ventilation installation is used only for the introduction of fresh air, the evacuation of air and smoke (in emergency situations) is done through natural ventilation shafts. The station also has smoke barriers, mounted at the level of the stairs that ensure access from the platform to the lobby. It is assumed that in the event of a fire, forced ventilation systems may not work or may be misused because service personnel cannot correctly identify the outbreak. Therefore, the possibility of using natural ventilation in emergency situations is being studied.

In the case of fire located in the lobby, with a power of 3 MW, the factors that most influence the effectiveness of natural ventilation are the total ventilation area and the height of the ventilation shaft. The basket effect cannot be obtained from this level due to the low height of the tunnel. Particular attention should be paid to the phenomenon of air absorption together with the smoke from the lobby, caused by too large an area of the tunnel mouth.

In the situation where the fire outbreak is at the level of the waiting platform, the solution of the multi-storey tunnels was proposed, which are interrupted at the level of the lobby. Their

efficiency depends very much on the position of the fire source, the most efficient distribution of which must necessarily include the area adjacent to the stairs. In order to obtain a stronger chimney effect, the smoke barriers must be as high as possible and all PSD doors must be closed. The smoke evacuation rate using this method is higher than the minimum rate imposed by the Chinese standards (where the study was conducted), therefore the conclusion of the study is that smoke evacuation can be achieved even in the absence of mechanical ventilation.

Luo et al. [42] studied the interaction of the mechanical ventilation installation with natural ventilation on a 3-level subway station configuration (basement 2, basement 1 and lobby with central atrium with the possibility of opening - natural ventilation). The study includes an experimental part using a 1/50 scale model of the station (and Froude scaling to reduce fire parameters), as well as numerical simulation using FDS. The first scenario of the research assumed that the fire outbreak is located in the lobby and has a power (HRR) of 800 kW (0.045 kW in the case of the model). The vents (air intake at the lobby level) were closed, the exit doors from the station opened and the size of the opening in the dome varied. The simulation results are almost identical to those of the scale experiment, the measured parameter being the temperature.

The second simulation (which no longer involves the use of the scale model) followed the CO concentration, in the case of the same fire in the lobby, under the dome, without natural ventilation. The differences between the scenario without ventilation of any kind (reference scenario), the scenario with the start of smoke extraction through the mechanical installation in the lobby, the previous hypothesis plus the introduction of fresh air at level 2 and the previous hypothesis plus the introduction of air were followed.. The results show a decrease in CO concentration with the start of mechanical ventilation and the introduction of fresh air at the two underground platforms, thus creating an overpressure that prevents CO from descending to the waiting platforms. The air flow introduced at the platform level is approximately equal to the air flow extracted from the lobby level.

The following simulation followed the same cases as the previous one, with the difference that natural ventilation was included. The conclusions were the same. The following series of simulations followed the effect of the size of the dome opening on the ventilation efficiency, correlated with the position of the hearth (in the centre of the station, under the atrium or on the side). The conclusion is that as the opening area of the atrium increases, the CO concentration decreases (in the case of the focus below the atrium). In the case of the lateral focus to the atrium, the dependence is lower.

In another article based on numerical simulations, Gao et al. [43] used a two-level underground station configuration and an atrium lobby, which also has an opening for natural ventilation. To validate the constructed numerical model, the authors reproduced the experiments performed by other researchers and compared 4 fire parameters (HRR, smoke layer temperature, smoke layer height and CO concentration) obtained from the simulation

with the values of the experimentally obtained parameters, the values obtained by the two methods proving to be very close.

The objective of the study was to verify the efficiency of two hybrid ventilation alternatives: alternative 1 when the mechanical installation is used both for the introduction of fresh air at the two underground levels and for smoke evacuation from the lobby, and alternative 2 when the mechanical installation is used only for extracting smoke from the subway station. The simulations performed target different sizes of the atrium opening (from 0 to 16 m²) as well as different smoke evacuation speeds through the ventilation installation.

Following the simulations, a decrease of the CO concentration in the atrium was found by 57% if hybrid ventilation is used compared to if only mechanical ventilation is used, and in the rest of the lobby the CO concentration is 3 times lower in the same assumption.

The decrease in CO concentration is dependent on the size of the opening in the roof of the atrium. There is also an inverse relationship between the speed of smoke evacuation through the mechanical installation and the amount of smoke discharged through the opening. The higher the rate of smoke extraction, the lower the amount of smoke naturally emitted, because the smoke rising forces must overcome the depression formed by the mechanical installation to reach the atrium and evacuate naturally.

Particular attention was paid by Zhang L. et al. [44] on how to check fire safety scenarios involving the evacuation of a large number of people from a subway station with an underground level (waiting platform) and a lobby. The authors specify that the factors that influence the evacuation the most are: the power of the fire (rate of development of the fire, the amount of smoke, toxicity and HRR), the constructive characteristics (plan, size and compartmentalization) and the human factor.

This study proposes a comprehensive framework for determining the worst-case scenario in the event of a fire, which includes numerical simulation, time available for safe evacuation (ASET), time required for safe evacuation (RSET) and decision-making based on multiple attributes (MADA). Thus, numerical simulations are used to study the evolution of fire throughout the construction, and MADA multi-attributive analysis is used to estimate ASET and evacuation assessment in critical nodes, thus performing a more complex fire risk assessment in different scenarios. The minimum conditions necessary for the safe evacuation of people, according to the criteria imposed by the legislation of China, are: the smoke temperature is lower than 140° C, the CO concentration in the air is lower than 1500 ppm and the visibility is minimal. 10 m.

Numerical simulation is used to identify the most unfavourable fire safety scenario and a Chinese subway station on which 4 fire scenarios are chosen is taken as a case study. The first scenario involves a fire at the platform, at the base of one of the stairs that connects to the upper level. The second scenario assumes that the fire outbreak is located at the level of the lobby, next to a staircase that descends to the waiting platform, and the third scenario targets a fire outbreak located at one of the exits from the subway station. In all three scenarios, the

power of the fire outbreak was 2 MW, scenario 4 being the only one that involves an outbreak with a power of 3 MW located at the lobby, next to a staircase that connects to the waiting platform. The most unfavourable scenario proved to be the last of those studied, in which the time available for the evacuation was less than the time required for this operation.

In order to validate the results, an in-situ experiment was performed in the metro station used as a model for the numerical model, where a 2 MW fire outbreak was generated and it was found that the fire parameters observed in the simulation have values very close to those measured during the experiment, proving once again that the results of numerical models are very close to the experimental results.

In the case of burning subway trains that manage to reach the station to facilitate the evacuation of passengers, there is the problem of ventilating the smoke as quickly as possible using the ventilation installations in that station. If there are several ventilation systems, such as the fresh air intake / exhaust system at the level of the waiting platform, the heated air exhaust system at the bottom of the tunnel - the level of the train rails and the smoke exhaust system in the ceiling tunnels, their mode of operation must be very well established so as not to favour an even faster spread of smoke in the station. Using the special Fire Dynamic Simulator (FDS) software, Hu et al. [9] conducted a series of simulations to determine the most efficient way to interact with ventilation systems in a subway station in China. To do this, they studied how to propagate smoke in four different scenarios, as follows: scenario 1 - when only the smoke extraction installation from the top of the tunnel starts, scenario 2 - when the installation from the top and the one from the side work simultaneously lower, at the level of the train tracks, scenario 3 - when the smoke extraction installation from the top of the tunnel starts and the installation at the platform level extracts the smoke and scenario 4 - when the smoke extraction installation from the upper part of the tunnel starts and the installation at the level of the platform introduces fresh air, in order to create an overpressure and to prevent the smoke from occupying the entire platform on which the passengers are evacuated urgently. After analysing the temperature distribution and visibility on the waiting platform, the authors concluded that the variant that ensures a maximum temperature in the smoke layer of 600 °C and a good visibility at a height of 1.8 m (conditions necessary for the evacuation of passengers) is the one in which the smoke extraction installation at the top of the tunnel and the one at the platform level operate - scenario 3. These results are not in line with the classical approach, which assumed that the solution with the introduction of air through the system was more efficient. ventilation of the platform to create overpressure and prevent smoke from spreading in this direction, the numerical simulations clearly showing that this procedure does nothing but decrease the visibility on the platform and drastically reduce the neutral plane of the smoke.

The efficiency of ventilation systems in emergency situations is often judged by the speed with which they ensure the evacuation of smoke from the burning space. Too low a speed would make it impossible to evacuate the smoke in a timely manner, and too high a speed would lead to the oversizing of the installation and thus to its increased operating costs. To

determine the optimal rate of smoke evacuation from a subway station, Zhang et al. [45] performed simulations using SDS, which tested the efficiency of the flue gas system at several operating speeds (3 ... 10 m/s). The validation of the numerical results was done through a scale experiment for a subway station built on two levels. The graphs of temperature variation and air velocity differ very little from simulation to experiment and suggest that the optimal smoke evacuation speed is 8 m/s, as 7.5 m/s does not ensure the ventilation of the space flooded with smoke in 360 seconds, and the speed of 10 m / s does not offer a significant difference compared to 8 m / s so as to justify an increased air flow (and thus a much higher energy consumption).

The article published by Wu et al. [46] studies the temperature distribution in a subway station with a single underground level - the waiting platform, built as a dome without a partition floor with the lobby on the ground floor. 3 positions of the fire source are considered, each with 5 different values of the heat release rate. The temperatures obtained in these simulations are compared with the values obtained from the empirical calculations of the researchers Alpert, Heskestad and McCaffrey, the results are very close. Also, graphs were made with longitudinal profiles of the smoke temperature under the ceiling, being proposed equations to describe the resulting parables through combinations of different models identified in the literature (Li, Heskestad, McCaffrey).

In the case of the fire in the middle of the platform, due to the construction features of the station, the smoke rises to the ceiling of the lobby, and the longitudinal temperature profiles can be determined by the relationship proposed by Li and McCaffrey:

$$\Delta T_x = 0,0761 \left(\frac{H}{Q^{2/5}} \right)^{-5/3} T_{\infty} (0,607 e^{-2,12x} + 0,413 e^{-0,07x})$$

where,

ΔT_x represents the smoke temperature rise in "x" [K],

H is the height to the lobby ceiling [m],

Q is the total heat release rate [kW],

T_{∞} is the environment temperature [K].

For the second scenario, when the fire is near the wall of the waiting platform, the smoke rises to the floor on the ground floor, after which a lateral movement begins, being restricted by the smoke curtains mounted on the ceiling of the platform. The mathematical relation proposed for the description of the smoke temperature distribution in this case is a combination of two previous relations proposed by Li and Heskestad:

$$\Delta T_x = 25 \left(\frac{Q_c^{2/5}}{H - z_0} \right)^{5/3} (0,46 e^{-2,55x} + 0,552 e^{-0,075x})$$

where,

Q_c is the convective rate of heat release [kW],

Z_0 is the virtual origin [m],

X is the distance from the fire source [m].

The third scenario is similar to the previous one, with the difference that the distance from the wall to the smoke curtain is longer, which is why it takes longer until the smoke reaches a one-dimensional flow.

The appropriate mathematical relationship for this scenario is a combination of the relationships previously determined by researchers Li and Alpert:

$$\Delta T_x = \frac{16,9 Q^{2/3}}{H^{5/3}} (0,299 e^{-2,232x} + 0,713 e^{-0,108x}) (x \leq 3,33)$$

$$\Delta T_x = \frac{16,9 Q^{2/3}}{H^{5/3}} (0,337 \left(\frac{H}{L}\right)^{1/3} e^{-0,079x \left(\frac{L}{H}\right)^{1/3}}) (x \geq 3,33)$$

where L is the height to the ceiling [m].

Another study based on experiment and simulation in FDS was conducted by Lee et al. [7] in a subway station in Tokyo, consisting of a single underground level - the waiting platform. The scenario proposed in the study targeted a fire at the store at the level of the waiting platform, for the realization of the experiment being used six sources of methanol, of 80 kW each.

The configuration studied by the metro station is a waiting platform and a lobby, with a mechanical ventilation system that, depending on the needs, introduces or evacuates the air from the station. The temperatures and concentrations of CO in the smoke layer were measured at different points on the platform, on the staircase and on the ground floor. These values were compared with those of the numerical simulation in the SDS, and the results showed differences of maximum 10°C. The numerical model being thus validated, the study authors went further and simulated fires of higher power, for longer periods of time, in which they could observe the effect of mechanical ventilation and smoke curtains installed at the level of the waiting platform. Without the ventilation system working and the smoke curtains being used, both levels of the subway station were flooded with smoke in about 400 s, which did not happen when the ventilation was turned on. The authors of the study were thus able to demonstrate the effectiveness of the measures to reduce the effects of the fire in the studied metro station.

One of the few numerical simulations performed in Fluent for the study of ventilation methods in a subway station is the one performed by Yucel et al. [47]. Their study concerns a configuration consisting of a tunnel connected to a waiting station / platform, in the middle of which is arranged the source of fire: a round tray with polypropylene. Variations in smoke temperature and velocity were measured, above and at different distances from the hearth, under conditions of longitudinal ventilation of 0.1 and 3 m / s in the tunnel, respectively. The critical speed was determined analytically at 1.4 and 1.43 m / s, respectively, a speed that was not reached in any of the three cases studied, given that the air speed decreased at the entrance from the tunnel to the subway station.

The highest temperature above the hearth is recorded when the longitudinal ventilation is stopped, the second is recorded with an air ventilation of 3 m / s and the lowest temperature could be observed at an air ventilation of 1 m / s. The explanation for the fact that the temperature increased with the increase of the air speed is that a stronger oxygenation of the hearth was achieved, which led to the intensification of the combustion and implicitly the increase of the temperature.

The values of the smoke layer temperatures obtained from the simulations differ from those obtained experimentally, most likely due to the simplifying assumptions used (fire radiation was not taken into account and the walls were considered isothermal), but mainly due to the turbulence model chosen. k- ω SST), which is not indicated for this type of application because it has problems in predicting turbulence levels and complex internal flows and does not take into account the effect of gravity on smoke.

3.2 Synthesis and conclusions

It can be seen that all the articles described above use numerical simulation as a research method to study the evolution of fire-specific parameters in tunnels and subway stations. In most articles, numerical simulation is the main study method, the other methods (theoretical analysis, small-scale experiments or real-scale experiments) being used to validate the results obtained numerically. At the same time, a small number of articles use numerical simulation as a secondary study method, to compare previously obtained results or to better visualize them.

Tab. 4 centralizes the articles presented in this chapter and highlights certain aspects related to the way of conducting the numerical study, its validation (where applicable) and the configuration of the tunnel or subway station studied. The most frequently monitored parameters are the critical speed, the backlayering distance, the maximum temperature in the smoke layer and the CO concentration.

Thus, we can see that 80% of the simulations have a structured discretization network, just as 80% also performed a verification of the discretization network before conducting the actual numerical study. Also, 65% of the articles use Large Eddy Simulation (LES) as a turbulence model, while 35% use the standard K- ϵ model or its modified forms. Regarding the validation of numerical results, only 60% are validated, of which 25% are validated by small-scale experiment. In addition, only 55% of the studied articles took into account the transmission of heat by radiation, the rest using simplified forms of calculation to approximate this amount of heat.

Tab. 4 Summary table of the documentary study on efficient ventilation solutions in emergency situations in metro stations and tunnels

Reference number	Type of mesh	Mesh test	Wall function	Turbulence model	Software	Results validated	Analytical validation	Previous experiments	Experiments in the study	Parameters	HRR [kW]	Radiation model	Studied configuration	Fire position
26	structured	yes	-	LES	FDS	yes	yes	-	Reduced scale	Temperature Visibility CO concentration	7,5	yes	Simple and double tunnel, inclined	Lowest point of the tunnel
27	structured	yes	-	LES	FDS	no	-	-	-	Temperature, Critical velocity	16,7	yes	Tunnel with train stopped inside	Before and after the blockage
28	unstructured	yes	standard wall function	k-ε turb model	Fluent 15.0	no	-	-	-	Temperature Air velocity CO concentration	30 MW	yes	2 stations and the tunnel between them	Train on fire in the tunnel
29	structured	yes	-	LES	FDS	no	-	-	-	Temperature CO concentration	4	no	Simple tunnel at altitude	Middle of the tunnel
30	structured	yes	-	LES	FDS	yes	yes	-	scale 1:10	Smoke temperature Air speed Backlayering distance	5 7,5	no	Simple tunnel	Middle of the tunnel
31	structured	yes	-	LES	FDS	no	-	-	-	Smoke evac velocity Time for smoke vent	7,5	no	Simple tunnel	Different distances from the entrance
32	structured	yes	-	LES	FDS	yes	-	yes	-	Max temperature Air velocity	5 7,5 10	yes	Tunnel with longitudinal ventilation system	Electrical compartment of the train, in tunnel
33	structured	yes	non-slip condition	LES	FDS	yes	-	yes	-	Max temperature Air velocity	8, 18, 30, 50 și 100	yes	Tunnel with longitudinal ventilation system	In the tunnel
35	unstructured	yes	standard wall function	RNG k-ε turbulent model	Fluent	yes	-	yes	-	Smoke temperature Critical velocity Backlayering distance	10	no	Simple tunnel	În mijlocul și în lateralul tunelului
37	structured, dynamic	yes	-	k-ε turb model	Fluent	-	-	-	-	Static pressure, Overpressure, Air flow rates, Air velocity	-	no	Tunnel with vent shafts	-
38	structured, dynamic	yes	-	standard k-ε	Fluent	yes	-	yes	-	Air velocity Air pressure	-	no	Double tunnel with natural vent shafts	-
39	structured/unstructured	-	-	LES și RNG k-ε model	FDS și Fluent	yes	yes	yes	-	Critical velocity	-	no	Simple tunnel	Different distances from the entrance
40	unstructured	yes	nonslip condition	buoyancy-modified RNG k-ε	STAR-CCM+	yes	-	-	scale 1:8	Temperature Air velocity O2 concentration	5 6	yes	Tunnel with mechanical ventilation system	Train on fire while moving
41	structured	yes	-	LES	FDS	no	-	-	-	Temperature Visibility CO concentration	3	no	Station with lobby and platform	3 different positions in the station
42	structured	-	-	LES	FDS	yes	-	-	scale 1:50	Temperature CO concentration	5	yes	Station on 3 levels	Different positions in the station
43	structured	yes	-	LES	FDS	yes	-	yes	-	Temperature CO concentration	7,5	yes	Station with 2 underground levels, 1 lobby and 1 atrium	Fire in the lobby
44	structured	-	-	LES	FDS	no	-	-	-	Temperature, Visibility CO concentration	2 3	yes	Stație cu un nivel subteran și un lobby	4 positions, on the lobby and the platform
45	structured	-	-	LES	FDS	yes	-	-	scale 1:50	Temperature, Visibility CO concentration	2	yes	Station with lobby and platform	Near the stairs
46	structured	yes	-	LES	FDS	no	-	-	-	Temperature	2,5	yes	Atrium style station	3 different positions in the platform
47	unstructured	yes	nonslip condition	k-ω SST	Fluent	yes	-	-	scale 1:10	Air velocity Max temperature	2 2,3	no	Tunnel and platform	Fire in the middle of the platform

4. Documentary study on smoke evacuation from metro stations equipped with safety doors (PSDs / PEDs)

Security doors or platform screen doors (PSDs) have the role of creating a physical barrier between the waiting platform and the tunnel through which trains run. They are made mostly of reinforced plexiglass and metal frame, extending from floor to ceiling, in the case of PSD type, or may have a lower height, in this case being platform edge doors (PEDs).

Although they began to be installed in 1987, there are very few studies on their operational safety in the event of a fire, especially how they affect the emergency ventilation system.

4.1 Studied articles

In the article published by Chen et al. [5], the authors study the effect of PEDs on smoke evacuation from a Taipei subway station. The station used as a model for numerical simulations has two underground levels, with an island-type platform and a lobby that connects to the outside. In order to give the impression of more space, the partition floor between the two levels was removed in the centre of the station, which makes it difficult to evacuate smoke in emergency situations. The station is equipped with a tunnel ventilation system that sucks air from the tunnel and blows it to the surface, inducing in the tunnel an air movement speed of 5 m / s, air ventilation system under the platform, which takes the heated and polluted air from the level of the train rails and the smoke evacuation system from the lobby, consisting of 8 uniformly distributed fans that induce a speed of air movement of approximately 2 m / s. In the event of a fire, the person in charge of the control centre decides which systems should be started, depending on the location of the outbreak and its development.

The first fire scenario involved a fire outbreak on the right side of the lobby, the smoke escaping naturally, due to the chimney effect, on the two stairs that connect to the outside. The same effect contributes to the evacuation of smoke in the case of the fire outbreak located in the left / right end of the waiting platform. If the fire is located in the centre of the platform, the smoke spreads to the lobby and endangers the lives of passengers, even if the smoke evacuation system is activated at this level. If the other two smoke evacuation systems are activated simultaneously, its spread is limited to the central area of the platform and no longer endangers the evacuation of passengers on the 4 stairs to the lobby. This is largely due to the fact that the tunnel ventilation system and the ventilation system under the platform generate a downward flow of air from the lobby to the platform, by sucking air from the platform.

The study also verified the hypothesis in which PSD doors are installed and proposed as a way to improve the ventilation strategy the opening of only 8 doors next to the fire source, simultaneously with the start of the two ventilation systems in the tunnel. In this way, the suction force of the air from the station into the tunnel is accentuated, achieving in a shorter time the smoke evacuation.

In case of a train fire stopped at the station, even if all PSD doors are open for emergency evacuation of passengers from the train on the platform, the simple installation of the doors has a major effect on preventing the spread of smoke on the platform, due to their constructive shape. The smoke retained in this way in the tunnel does not endanger people's lives and is then evacuated through the tunnel's ventilation system.

A comparative study between the efficiency of PSDs and PEDs was conducted by Meng et al. [48]. They performed a small-scale experiment and numerical simulations to determine the maximum temperature in the smoke layer and the longitudinal distribution of temperature in the tunnel in case of a fire in a train in the tunnel. In this way they could observe that in the case of installing PEDs type doors the maximum temperature in the smoke layer is lower and the temperature drop in the longitudinal plane is more accentuated, most likely because the smoke spreads under the ceiling of the waiting platform.

If PEDs have smoke curtains that can go down in the event of a fire, they behave similarly to PSDs. This was investigated by Meng et al. [49] using numerical analysis, for the scenario of a train on fire at the station. Their study shows that the best smoke evacuation results are obtained if the lobby air intake system, the platform air exhaust system and the tunnel air exhaust system are activated, while deactivating the exhaust system under the platform and the air intake system at the platform level. This ventilation strategy generated the best smoke evacuation results from those investigated, regardless of the type of doors used.

Li and Zhu [50] studied the impact of PSD doors on smoke evacuation in the event of a fire in the center of the waiting platform. Normally, if there is no train in the station from which passengers are disembarked / disembarked, the doors of the PSDs are closed, greatly reducing the space in which the smoke can disperse. By opening the doors on both sides of the island-type platform, smoke is sucked into the tunnel's smoke system, improving visibility at the station and lowering the temperature of the smoke layer, thus improving passenger evacuation conditions.

Hu et al. [9] investigated the most effective way to cooperate with smoke extraction installations at the level of the tunnel and the platform of a metro station, in case of a train fire stopped at the station. The station is equipped with PSDs that are open for emergency disembarkation of passengers. The study authors analysed and compared the distribution of smoke temperature and visibility on the platform and concluded that the best ventilation strategy is provided by activating the suction system in the tunnel ceiling and the suction system on the platform, while disabling the exhaust system under the platform.

The effect of PSD / PED systems on smoke evacuation from a subway station was also studied by Wang et al. [51], by performing 24 simulations corresponding to an equally large number of possible scenarios, generated by the alternative use of ventilation systems. The best smoke evacuation solutions for the analysed configuration were obtained by optimizing the closing/opening of the PSD doors and the doors at the end of the subway platform, correlated with the use of ventilation devices (from the upper floor - lobby, from the platform, above

the train lines, at the level of the train lines and the fans in the subway tunnels). Of particular importance was the introduction of air on the upper floor and the extraction of smoke on the platform and subway lines. It is also more efficient not to start the fans on the subway lines if the PSD doors are open, but it is recommended to open them when the doors at the end of the subway platform are open. Therefore, closing / opening the doors of PSDs / PEDs depends very much on the position of the hearth and the ventilation systems available in the station, the most efficient smoke solutions being determined according to the proposed fire scenario.

Also in favour of installing PSD doors is the study published by Roh et al. [52] which, although simpler in terms of the model created and the scenarios studied, reaches the same conclusion: the longest period of time until conditions are reached that no longer allow the safe evacuation of persons is obtained in the case of simultaneous use of PSD-type systems and ventilation systems (from the tunnel and from the platform). An important aspect to consider is the fact that the PSD doors in the immediate vicinity of the train outbreak were scheduled to "break" after 90 seconds, during which time they did not allow the smoke to spread in the subway station. When using PSD doors and ventilation systems, the time available for evacuation increases by 350 s compared to the scenario without PSD doors and without ventilation (for the studied configuration).

A less studied ventilation strategy is natural ventilation, which is the subject of the study by Wu et al. [53]. They proposed a natural ventilation model for a subway station with two underground levels and PSDs door systems. Their results showed that the most important factors for efficient lobby ventilation are the total ventilated area and the height of the ventilation shaft. The higher the wells, the more accentuated the chimney effect and thus increases the smoke flow. For the ventilation of the platform, a system of out-of-phase wells is proposed, which ensures the formation of the chimney effect necessary to evacuate the smoke without the need for continuous constructions that run through the lobby to connect the platform with the outside. However, in order to strengthen the chimney effect at the platform level, the doors of the PSDs need to be closed and not allow the air in the tunnel to affect the negative pressure that is created by eliminating the smoke from the platform level.

The effect of PSD doors on the evacuation of smoke and pollutants in the event of a fire in a subway station with three underground levels was studied by Jung et al. [54]. They analysed 8 emergency scenarios in which the operating conditions of the smoke installation at the level of the platform and the way of closing / opening the PSDs doors varied. The results of the simulations showed that by opening the doors PSDs increase the concentration of CO that reaches the waiting room (the highest level of the station), as well as the degree of spread of the pollutant throughout the station.

4.2 Synthesis and conclusions

The number of articles on emergency smoke ventilation in subway stations equipped with PSDs doors is small, especially due to the fact that researchers have focused on other issues related to the comfort of people in the station, the degree of air pollution, sound insulation of PSDs doors etc.

In Tab. 5, the articles presented in this chapter were centralized and some aspects related to the numerical simulation, the validation of the obtained results, the parameters followed in the simulation and the configuration of the studied metro stations were highlighted. The most monitored parameters are the maximum temperature in the subway station, the speed of the ventilated air, the visibility limit and the CO concentrations.

Thus, we can observe that 88% of the studies use a structured discretization network, 55% performed a verification of the independence of the discretization network, 77% use the LES turbulence model, 66% did not validate the results through any other form of study, while 22% performed small-scale experiments to validate the results obtained numerically.

Tab. 5 Summary table of the documentary study on smoke evacuation from metro stations equipped with safety doors (PSDs / PEDs)

Reference number	Type of mesh	Mesh test	Turbulence model	Software	Results validated	Analytical validation	Previous experiments	Experiments in the study	Parameters	HRR [MW]	Studied configuration	PSDs/PEDs	Fire position
5	structured	-	Standard k-e	CFX4	no	-	-	-	Smoke velocity Smoke temp CO concentration	5 10	Station with 1 underground level	PSD and PED	3 positions on platform and train on fire
9	structured	-	LES	FDS	no	-	-	-	Temperature Air velocity	2	Station with underground platform	PSD	Train on fire in the station
48	structured	-	LES	FDS	yes	-	-	scale 1:10	Max temperature Temperature field	2 5	Train on fire near the station	PSD and PED	Train on fire in the station
49	structured	yes	LES	FDS	no	-	-	-	Smoke temperature Visibility limits	10	Station with underground platform	PSD	Train on fire in the station
50	structured	-	LES	FDS	yes	yes	-	-	Smoke layer height Max temperature	0,7	Station with underground platform	PSD	In the middle of the platform, between the stairs
51	structured	yes	LES	FDS	no	-	-	-	Temperature field CO concentration Smoke layer height Visibility limits	2,5	Station with underground platform	PSD	3 positions on the platform
52	structured	yes	LES	FDS	no	-	-	-	Visibility limits Evac time	35	Station with 3 underground levels	PSD	Train on fire in the station
53	structured	yes	LES	FDS	yes	yes	-	-	Smoke layer height Smoke velocity	3	Station with underground platform	PSD	3 positions on the platform
54	unstructured	yes	Standard k-e	ANSYS Fluent 13.0	no	-	-	-	Max temperature CO distribution	5	Station with underground platform	PSD	On the platform

5. Conclusions and perspectives

Ensuring the fire safety of ever-expanding subway networks is a challenge for both network administrators and academia, which is trying to keep pace with development requirements and propose efficient and modern solutions to prevent and manage the consequences of an emergency situation in this type of construction.

Given the challenges of conducting full-scale experiments in tunnels and subway stations, numerical simulations are the optimal solution for testing ventilation strategies proposed by engineers to make smoke evacuation more efficient in the event of a fire.

Fire safety regulations of some countries (Italy and USA) require CFD simulations to verify scenarios involving the activation of the ventilation system in emergency situations, before performing in-situ tests. In this way, only the scenarios that pose special problems in smoke extraction can be chosen for field verification, thus validating the numerical results obtained previously.

Most of the articles under consideration study the parameters of tunnel fires and use numerical modelling as the main study method, the validation of the results being done through theoretical analysis, small-scale experiments or, in very few cases, real-scale experiments. The results thus obtained contribute to the development of general knowledge in the field but especially to the identification of customized fumigation solutions for the configurations of studied stations and tunnels.

Regarding the regulation of the use of PSD / PED type doors, the only norm that refers to them is NFPA 130 from the USA, mentioning that they represent an effective option for ensuring comfort in the station and smoke control in tunnels, if the structural strength and durability on fire they are close to those of the subway liner. It is mentioned, however, that attention must be paid to the access of people from the tunnel on the platform in case of a fire that involves evacuation from the tunnel to the station and prepared measures in this regard.

Numerical studies involving the use of these systems as an integral part of the ventilation strategy are few, focusing on identifying the optimal solution for closing / opening the doors to achieve efficient smoke ventilation, in order to safely evacuate passengers from the train and station.

The conclusion of the studies is that the simple installation of PSD safety systems contributes to reducing the spread of smoke from the tunnel on the platform (in case of a fire at the train set), due to the fact that the upper part of the frame on which they are mounted acts as a smoke curtain.

In addition, in the event of a fire on the platform, by organizing the doors open, the chimney effect of the stairwell can be accentuated (for a natural smoke evacuation), the smoke evacuation can be forced in a certain part of the station (by activating the evacuation of smoke

from the tunnel and the opening of a limited number of doors to create a stronger draft) or the access of fresh air from the tunnel may be limited to slow the spread of the fire.

Given the small number of articles on the impact of installing PSDs / PEDs on smoke ventilation in emergency situations in subway stations, it may be considered appropriate to study these issues on the configuration of the Bucharest subway network to identify the best solutions to correlate the operation of the smoke installation with the organized opening of the doors. Also, in case of updating the specific domestic legislation (since 2002, respectively 2006), we consider it appropriate to provide for the obligation to verify fire response scenarios by performing CFD simulations by institutions / operators specialized in this regard.

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