FIRE STRATEGY STUDIES FOR THE BUCHAREST METRO

In the feasibility study and design of a metro project, the safety concept represents an essential technical and financial issue. Driving key design choices, a high-level fire safety strategy has to be developed from the beginning.

A good example on how a safety audit is carried out and a fire strategy is developed is the extension of metro line M4 in Bucharest, Romania. Dr Marco Bettelini, Director of Safety and Ventilation from Amberg Engineering, explains the roles of the parties involved, the identification and management of dangerous situations, and the definition of criteria for the protection of human life – all under the consideration and proper integration of the relevant regulations. This allows the identification of fire safety measures and criteria for safety management during design, construction, operation and maintenance of the metro line and ensuring an appropriate integration of fire safety in the whole process.

The project in Bucharest

Bucharest's metro consists of six lines which transport 720 000 passengers each day. The existing section of line M4 is located in the north-west of the city centre. Operator Metrorex plans an extension to the south of the city with another 13 stations and a total length of 11.6km (7.2 miles).

The Terms of Reference for this project foresaw the following main focus points for the investigation: Passenger evacuation and tunnel fire regulations as well as the ability to upgrade the safety installation to a headway of 90 seconds, double the current frequency. Furthermore, the possible future switch to a driverless system should be considered. At the end of the safety audit, a report addressed issues where international good practice or standards are not met.

The approach of the safety audit

The overall safety of a metro depends on the interaction of users, infrastructure, rolling stock and operations, so for the audit it is relevant to create a proper situation analysis of the whole system. All safety-relevant aspects like the infrastructure and equipment in the stations and tunnels, the rolling stock as well as organisational and operational procedures for normal and emergency operations are described. The analysis in Bucharest showed that, despite the structure and equipment of some stations being older, the system is generally in line with the current practice.

The average train speed on line M4 is 36km/h (22mph), although speeds of up to 80km/h (50mph) can be reached between stations; in 2018 the line carried 250 000 passengers between Monday and Friday. Replacement of rolling stock, built between 1978 and 1992 and refurbished in 2011-14, is ongoing.

Safety in line with the regulations

Before diving deeper, comparing the relevant national regulations with the international state-of-the-art in metro safety is crucial. The national regulation issued by the Romanian Ministry of Interior and Administrations regarding design, execution and maintenance of metro facilities is applied for civil protection. Furthermore, the MPLAT order 1065/2002 specifying construction design and associated installations regarding prevention as well as the detection of fires comes into play.

These two national regulations are supplemented by international NFPA (National Fire Protection Association) regulation 130. Since Romanian legislation allows for the use of other technical rules as long as they improve upon Romanian requirements, a combination of national and international regulations is possible.

Identification of possible risks

To assess safety on line M4, the risks are identified in a semi-quantitative evaluation in terms of frequency and possible consequences: i.e. the number of possible victims. The results are then visualized in a risk matrix, which ranks and identifies the scenarios requiring further analysis.

In Bucharest, the following scenarios were adopted for the safety audit:

Nr.	Incident Scenario	Frequency	Consequence	Risk Acceptance Category
1	Long standstill in tunnel	C	I	negligible
2	User's personal incidents	B	II	undesirable
3	Derailment during normal operation	C	II	tolerable
4	Collision between trains	D	III	tolerable
5	Small fire in technical room	B	I	tolerable
6	Small fire under train with train stop in station	C	I	negligible
7	Small fire on train with train stop in station	C	I	negligible
8	Large fire on train with train stop in tunnel (off peak occupancy)	E	IV	undesirable
9	Large fire on train with train stop in tunnel (rush hour)	E	V	undesirable
10	Large fire on train with train stop in station (off peak occupancy)	D	III	tolerable
11	Large fire on train with train stop in station (rush hour)	D	IV	undesirable
12	Electric shock during evacuation	E	II	negligible
13	Earthquake	C	II	tolerable
14	Flooding	D	II	negligible

FIGURE 1

Frequency		I marginal	II significant	III critical	IV serious	V catastrophic
A	Frequent	Undesirable	Intolerable	Intolerable	Intolerable	Intolerable
B	Likely	Tolerable	Undesirable	Intolerable	Intolerable	Intolerable
C	Occasional	Tolerable	Tolerable	Undesirable	Intolerable	Intolerable
D	seldom	Negligible	Negligible	Tolerable	Undesirable	Intolerable
E	Unlikely	Negligible	Negligible	Negligible	Tolerable	Undesirable
F	Rare	Negligible	Negligible	Negligible	Negligible	Tolerable

Consequences

FIGURE 2

> **"The overall safety of a metro depends on the interaction of users, infrastructure, rolling stock and operations, so for the audit it is relevant to create a proper situation analysis of the whole system."**

1. **Long standstill in tunnel:** Because of a defect in the traction power supply, the train comes to a halt in the tunnel. Supervised evacuation, no person harmed.
2. **Personal incidents:** A drunk person falls onto the track and is hit by an oncoming train. One fatality.
3. **Derailment during normal operation:** A train derails due to a technical defect and two coaches collide with the tunnel wall. A few severely and lightly injured passengers who are difficult to evacuate.
4. **Train collisions:** Two trains collide in the tunnel and partially derail. Multiple severely-injured people and a few fatalities. Rescue is difficult due to limited accessibility.
5. **Small fire in a technical room:** A fire starts inside a technical room; smoke escapes and fire damages parts of the tunnel equipment. The platform is evacuated, no-one is harmed.
6. **Small fire under train in a station:** A hydraulic pipe under the carriage catches fire. At a station, passengers alarm the metro staff and evacuation is initiated. Staff contain the fire. No-one gets hurt.
7. **Small fire inside the train at a station:** Luggage on a train begins to burn. The passengers contain the fire using fire extinguishers. Some minor injuries due to smoke inhalation.
8. **Large fire inside the train in a tunnel (off-peak):** Luggage on a train begins to burn and the fire propagates to the furniture. The train must stop 100m before the next station and passengers exit in both directions. Some are injured while jumping off the train.

9. **Large fire inside the train in a tunnel (peak occupancy):** Similar scenario as before, but it is rush-hour and the train stops between two stations. Passengers evacuate in both directions on the walkway. Some persons get injured.
10. **Large fire inside the train at a station (off-peak):** Same scenario, but the train can continue to the next station. There, the passengers start the evacuation themselves. More than ten severely injured people, fatalities possible.
11. **Large fire inside the train at a station (rush hour):** Same scenario, but the train can continue to the next station. This time the platform is full of people and another train has stopped on the opposite track. Passengers of both trains start evacuating. The egress route is congested.
12. **Electric shock during evacuation:** During an emergency procedure, in any of the scenarios including an evacuation, a person gets an electric shock from the third rail and dies.
13. **Earthquake:** An earthquake derails a train, but the tunnel and the station do not collapse. Some people lightly injured, but a difficult evacuation.
14. **Flooding:** A burst dam floods the city. This is a comparatively slow process with significant material damage, but still dangerous for people inside the metro. Up to ten injured persons and one fatality.

Next, these risks are classified (see figure 1). Incident statistics for one specific metro system are generally too weak to be used directly, so experiences from comparable metros complement the analysis. Unknown data is estimated based on the expert judgement of the safety engineers. All scenarios are assessed in terms of frequency and consequences and visualised in a risk matrix (see figure 2). The risks are categorised as either 'Intolerable', 'Undesirable', 'Tolerable' or 'Negligible'. Intolerable risks require immediate mitigating measures, whereas the three others could be acceptable with the agreement of the metro authority. The ranking for line M4 shows that there are no 'Intolerable' risks.

Fire scenarios 8, 9 and 11 are 'Undesirable': While their probability is low, these scenarios have enormous consequences since self-rescue is difficult and can result in significant casualties. The self-rescue depends on fire dynamics and smoke propagation, evacuation supporting measures such as the ventilation system, train evacuation facilities and egress routes. Mitigating measures shall be carefully evaluated for such scenarios.

Scenario 2, a user's personal incident, is also classified 'Undesirable' and these incidents should be minimised. Possible solutions include Platform Screen Doors (PSD).

Scenarios 3, 4, 5, 10 and 13 fall into the 'Tolerable' category. Additional safety measures are not mandatory, provided that the metro operator accepts them. The level of risk from scenarios 1, 6, 7, 12 and 14 is classified as 'Negligible'.

Analysis of 'Undesirable' fire scenarios

Analysing the risk scenarios shows that the large fire scenarios need further investigation. A mid-size fire scenario is assumed, with a peak heat-release rate of 15MW and a development time of 15 minutes. This is representative for rolling stock at least partly-compliant with current regulations for fire resistance and 'normal' ignition energy. The self-rescue scenarios account for low (130 people in case of a train stop at a station, 100 in the case of a stop in the tunnel) and high occupancy (1300 in the station and 1000 in the tunnel).

In case of fire, trains should proceed to the next station whenever possible. In these conditions, the station's ventilation system is activated in maximum extraction mode and the intermediate ventilation stations located between stations support this procedure with maximum air injection.

The evacuation of a station in Bucharest requires, according to the simulation, between 5min 20secs and 5min 50secs. The simulated evacuation of the platform is around 3min 45secs and four minutes. This shows that the self-rescue facilities are fully adequate.

Safety and ventilation in fire scenarios

The scenario of a fire in the train stopped in a tunnel has a low likelihood. It is critical and requires specific ventilation, self-rescue and intervention strategies. The stations on line M4 are spaced between 540m and 1527m apart. All stations and intermediate ventilation stations are equipped with a reversible ventilation system with a capacity of 400 000m^3/h (111m^3/s); this is sufficient for generating a longitudinal air velocity of about 2m/s in the empty tunnel.

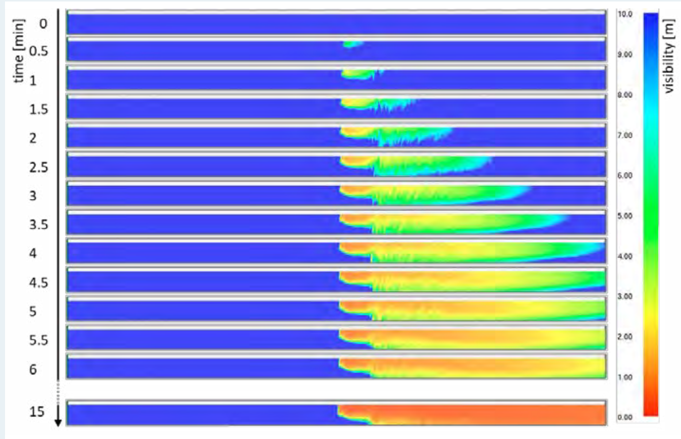

FIGURE 3 **Train fire in tunnel with longitudinal ventilation of 2m/s from left to right, including a representation of visibility length in the tunnel (side view) at different time intervals. The vertical dimension is stretched ten times.**

The ventilation strategy is based on generating a longitudinal air flow in the most favourable direction – self-rescue and intervention are carried out from the opposite direction. Figure 3 (above) shows the evolution of visibility conditions in the tunnel. The results show that the critical velocity at the fire location is achieved. Therefore, no backlayering occurs and the conditions upstream of the fire are ideal for self-rescue and intervention. In this scenario, proper co-ordination between ventilation, self-rescue and intervention is essential.

Results of the audit and the meaning for Bucharest Metro

All results of the audit are fully acceptable but suggest possible improvements, which are being investigated for the planned extension. In case of fire in the stations, facilities for self-rescue are adequate although additional measures for improving smoke management could be useful, including an increase of the smoke-extraction rate. The analysis proved that measures such as PSDs, coupled with smoke curtains at the bottom of stairways and optimisation of the station's architectural layout, show a comparable effectiveness.

The current safety concept in case of fire with the train stopping in a tunnel is based on self-rescue and intervention at track level. Mobile ladders for overcoming the height differences shall be put in place before self-rescue can begin. An alternative concept under investigation for the upcoming purchase of new rolling stock is the evacuation through either train extremity and self-rescue over the space between the tracks. A more effective solution would be the construction of elevated walkways. This would be more expensive but could allow for significantly lower self-rescue times and more efficient intervention.

The investigation resulted in a series of maintenance measures for the existing equipment and a list of propositions for improving the overall safety level. These additional measures are classified according to priority and some need to be implemented as soon as possible across the whole system; others are necessary but can be postponed and integrated within the next refurbishment. That affects measures related to infrastructure, rolling stock, equipment or organisational aspects.

Part of these measures, such as PSDs, could be implemented in the preliminary design of the planned extension, while others, such as fully-equipped elevated walkways, will be analysed and discussed in more detail. As a mid-term objective, the investigation of the systematic applicability to the whole network is pending.

The construction of the extension of line M4 is estimated to be completed within five years from the commencement of the works.

› *This article was compiled by Dr. Marco Bettelini, Director Safety and Ventilation, Amberg Engineering; Constantin Muståţea, Technical and Investment Director, METROREX SA; and Roger Schaad, Content Marketing Specialist, Amberg Group.*