Self-Rescue in Traffic Tunnels - Applications

M. Bettelini
Amberg Engineering Ltd., Regensdorf-Watt, Switzerland

ABSTRACT: Self-rescue represents the most important and critical safety element in case of fire in underground traffic infrastructures. State-of-the-art simulation tools allow for a comprehensive simulation of fire scenarios in traffic infrastructures. This paper focuses on sample applications of the combined simulation of fire scenarios, traffic management, smoke propagation and self-rescue in underground traffic infrastructure. Selected key issues, such as the interaction between emergency exits and tunnel ventilation, are reviewed based on real-life examples for road and rail tunnels.

1 INTRODUCTION AND OBJECTIVES

Self-rescue is in key safety principle if modern traffic infrastructures. All persons involved in an emergency should be able reaching a safe location within a few minutes. Self-rescue should generally be completed before the first responders arrive on site. Their primary roles are generally to rescue injured persons or persons with reduced mobility and controlling the fire.

The simulation of self-rescue is an essential component of safety design and safety verification. Relevant fire scenarios are analyzed for assessing the times required for self-rescue and verify if tenable conditions can be provided during the whole process. This requires a careful analysis of person motion and smoke propagation. The outcome of the analysis depends most directly on number and location of emergency exits as well as ventilation design and control.

One-dimensional (1D) simulation is a well-established approach for the comprehensive analysis of fire scenarios in tunnels. All relevant effects, such as tunnel aerodynamics, traffic, fire, emergency ventilation and person motions, can be modeled in very realistic manner. 1D simulation is significantly more rapid and inexpensive than 3D simulation. The price to be paid is a loss of detail, particularly concerning smoke propagation and stratification.

The simulation approach used herein was presented by Bettelini (2011, 2023). This paper focuses on practical applications for road and rail tunnels.

All simulations presented herein were carried out using version 4.8 of the Author's code TunSim. This tool is being used since over two decades for design and design verification of road and rail tunnels worldwide.

2 ILLUSTRATIVE APPLICATION FOR ROAD TUNNELS

2.1 *Tunnel definition*

The analysis and results shall be illustrated based on a hypothetical Alpine tunnel with the following real-life characteristics:

- Length 1500 m, longitudinal slope 5%

- Ventilation systems: natural ventilation, longitudinal ventilation, semi-transverse ventilation with concentrated smoke extraction (rapid activation, 90 s after fire onset)
- Cross section 65 m^2 (no smoke extraction) and 55.3 m^2 (with smoke extraction)
- Hydraulic diameter 8.0 m (no smoke extraction) and 7.35 m (with smoke extraction)
- Emergency exits every 500, 250 or 125 m
- 600 veh./h downwards, 300 veh./h upwards
- Velocity 60 km/h, 10% HGV
- Peak fire intensity 30 MW, developing linearly from 0 to 30 MW within 10 min
- Tunnel closure 90 s after fire onset
- Alert to the user with request to leave the tunnel at 90 s

In all the following images the positive direction is from left to right and the upper portal is at the left, with a uniform longitudinal slope of -5% from left to right.

2.2 *Natural ventilation*

Full results of the analysis with natural ventilation, considering emergency exits every 500 m, are presented in Figure 1 to Figure 4.

Figure 1 shows the evolution of longitudinal air velocity and smoke propagation. Before fire onset the air velocity is directed from left to right, in downwards direction. This is due to the traffic conditions considered. After fire onset, at t = 0, the traffic effect decays rapidly, and the thermal effect of the fire induces a powerful flow reversal. Smoke reaches the left (higher) portal 8-9 min after fire onset.

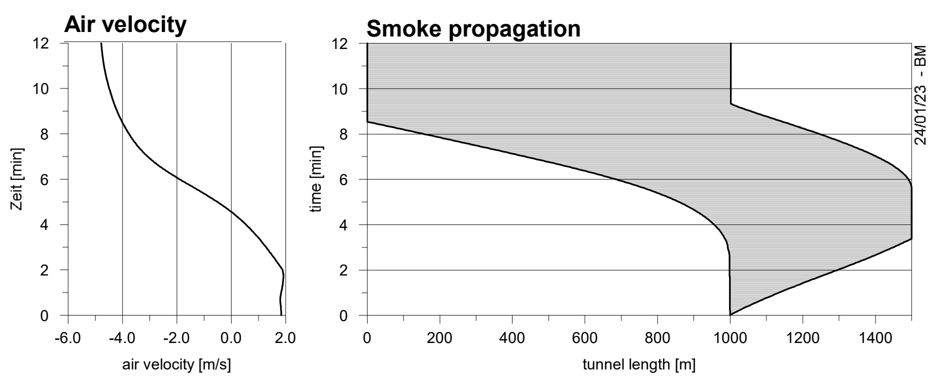

Figure 1. Natural ventilation - Longitudinal air velocity (left) and smoke propagation (right).

Figure 2 shows the vehicle trajectories and the number of vehicles trapped in the smoke. The vehicles approaching the fire are stopped, while the vehicle which already passed this location can leave the tunnel undisturbed.

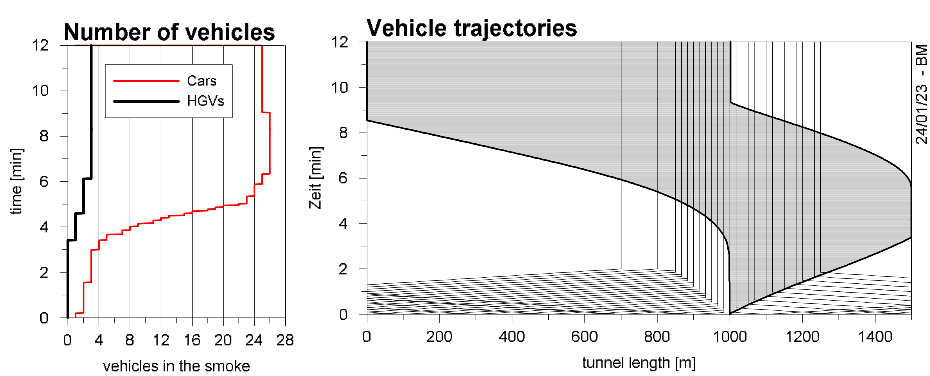

Figure 2. Natural ventilation - Vehicle position in time (right) and number of vehicles in smoke (left).

Figure 3 and Figure 4 show the evolution of the self-rescue process. It is important noticing that in this case an escape trajectory per vehicle is shown, since generally the occupants of a car escape jointly. Different conditions obvious apply for buses, which shall not be accounted or in this paper.

The person trajectories, starting from the blocked vehicles, are illustrated on the right. Several important effects can be recognized. The fire almost immediately blocks the emergency exit located at 1000 m. Self-rescue for the persons in the immediate vicinity of the fire starts almost immediately (30 s preparation time) and is directed away from the fire. Left of the fire, it is clearly recognized, how the initiation of self-rescue is triggered by the escaping persons. This “herd effect” is well known from empirical research and practical experience. Persons located at larger distances react short time after the alert is issued. Self-rescue for the persons on the right of the fire is triggered by the approaching smoke. The escape trajectories clearly illustrate the impact of visibility and smoke inhalation. In smoke-free areas, escape occurs with an average speed of 1 m/s (input value). Escape velocity rapidly drops as soon as the persons are reached by the smoke and further drops with increasing smoke inhalation. If an emergency exit cannot be reached in time, escaping persons are incapacitated and stop.

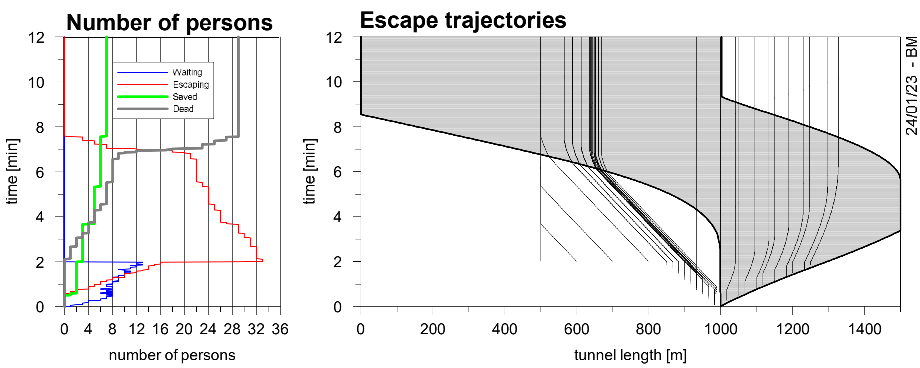

Figure 3. Natural ventilation - Person position in time (right) and self-rescue evolution (left).

The right side of Figure 4 provides a closer analysis of the unsuccessful escape histories. A triangle marks the starting and a cross the final position of all incapacitated persons. This provides important insight for improving safety. The most obvious paths for improvements, ventilation and reduced distance between emergency exits, shall be explored in the following sections.

The left-hand side of Figure 3 and Figure 4 shows important statistical information of the progress of self-rescue. The time evolution of the number of persons waiting, escaping, in safety or incapacitated is presented. Initially most persons are still either in motion or waiting in their vehicles. Around 2 min after fire onset, after alert and a short preparation time, the self-rescue process starts everywhere in the tunnel. A turning point is reached around 7 min after fire onset, as smoke reversal impacts several persons escaping to the left.

Figure 4. Natural ventilation - Person position in time (right) and self-rescue evolution (left).

2.3 *Influence of distance between emergency exits*

Figure 5 illustrates how additional emergency exits can improve the situation. A reduction of the distance between emergency exits from 500 to 250 m shows limited benefits for the persons on the right-hand side of the fire, which are trapped by the rapid initial smoke propagation due to traffic. Conversely, additional emergency exits are very helpful on the left-hand side, where all escaping persons can safely reach an emergency exit before being reached by the smoke front. Generally, reduction of the distance between emergency exit represents an excellent safety measure in case of large tunnel slope.

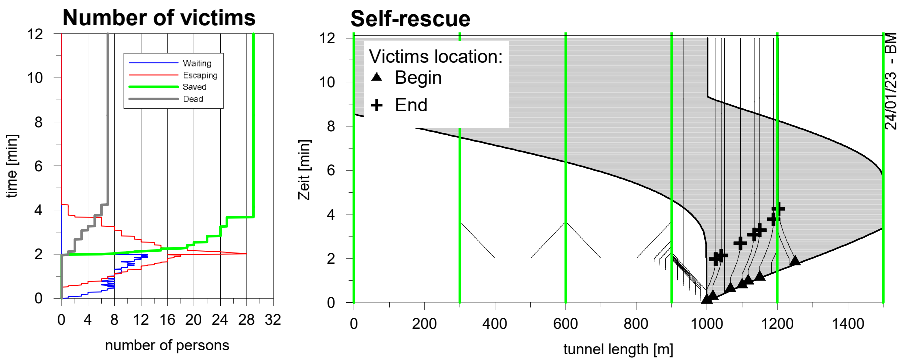

Figure 5. Natural ventilation, emergency exits every 300 m - Person position in time (right) and self-rescue evolution (left).

A further reduction of the distance between emergency exits from 300 to 150 m provides additions benefits, as shown in Figure 6.

These sample results illustrate an important finding with general validity: a distance of 500 m between emergency exits is generally not acceptable for tunnels with large longitudinal slope.

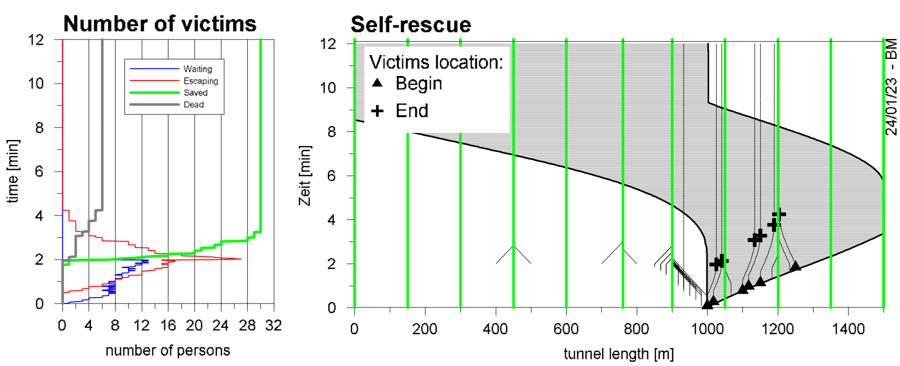

Figure 6. Natural ventilation, emergency exits every 150 m - Person position in time (right) and self-rescue evolution (left).

2.4 *Choice of ventilation system*

Longitudinal ventilation provides the possibility of mastering the longitudinal air velocity and thus slowing down smoke propagation. As shown in Figure 7, this is particularly useful for reducing the negative effects of the reversal of smoke propagation. The benefits in case of bidirectional traffic coupled with large longitudinal slope are significant, but intrinsically limited.

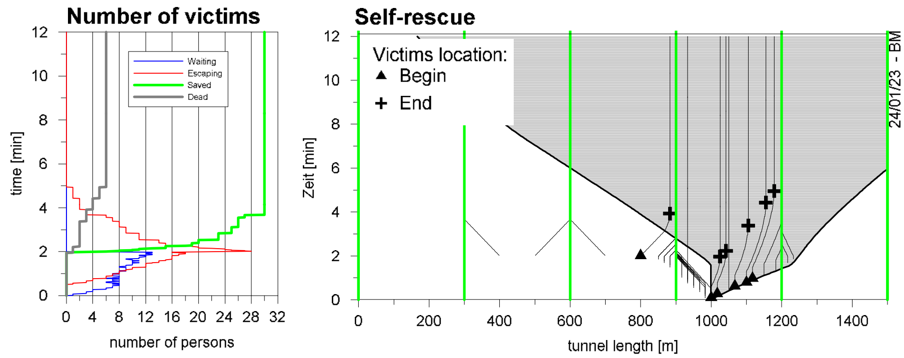

Figure 7. Longitudinal ventilation (6 groups x 2 jet fans, static thrust 2400 N per unit), emergency exits every 300 m - Person position in time (right) and self-rescue evolution (left).

The adoption of a ventilation system with concentrated smoke extraction provides the potential for a significant reduction of smoke propagation, as shown in Figure 8. In this particular case it can be seen that the combined effect of reduced distance between emergency exits and smoke extraction results in a very significant improvement of self-rescue conditions. The only residual victim is a person, which was directly involved in the fire.

Figure 8. Semi-transverse ventilation (extraction rate 3 m/s x tunnel cross section) with concentrated smoke extraction, emergency exits every 300 m - Person position in time (right) and self-rescue evolution (left).

This short analysis illustrates the power of 1D simulation of fire scenarios and detailed self-rescue analysis for road tunnels. The analysis of selected scenarios can be used for identifying potential safety issues and avenues for improvements. In this context, some lack of precision due to approximate modeling of smoke stratification etc. only represents a minor concern.

3 ILLUSTRATIVE APPLICATION FOR RAIL TUNNELS

3.1 *Tunnel definition*

A hypothetical double-track rail tunnel shall be defined for illustrating the analysis of self-rescue in a rail tunnel. The tunnel characteristics are:

– Length 5000 m, longitudinal slope 1%
– Natural ventilation systems
– Cross section 100 m^2
– Hydraulic diameter 10.0 m
– Emergency exits at 1000, 500 or 250 m
– Passenger trains: length 400 m, speed 120 km/h
– Freight trains: length 800 m, speed 80 km/h

– Fire on a passenger train, located at the center
– Peak fire intensity 10 MW, developing linearly from 0 to 10 MW within 10 min

In all the following images the positive direction is from left to right and the upper portal is at the right, with a uniform longitudinal slope of 1% from left to right.

3.2 *Reference scenario*

The reference scenario is presented in Figure 9. The fire train enters at t = 0 with a speed of 120 km/h. It stops after 75 s at 2500 m from the entry portal. Further trains follow: a freight train enters 2 min later with a speed of 80 km/h. This train is stopped 2 min after stop of the first train, 3.25 min after entering the tunnel. A further passenger train enters from the opposite portal 1 min after the fire train. The trains not directly impacted by the fire are stopped and reversed 5 min after stop, with a speed reduced to 30 km/h. This reduction has the objective of limiting the aero-dynamic disturbance to smoke propagation. The complex evolution of longitudinal air velocity and the corresponding smoke-propagation patterns are presented in Figure 9.

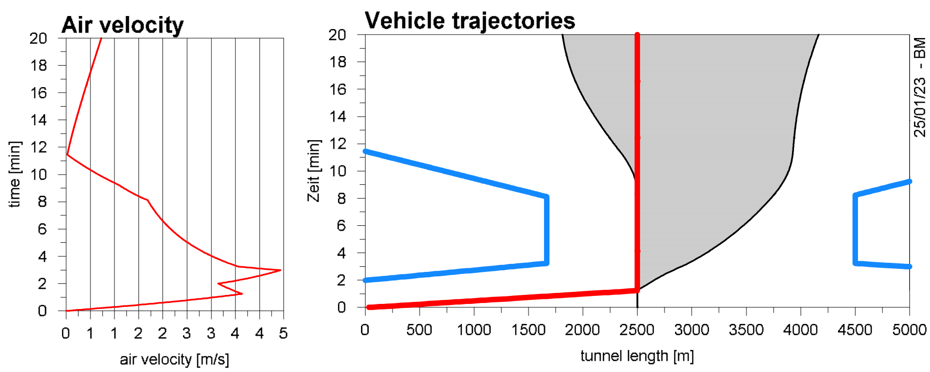

Figure 9. Train motion, longitudinal air velocity and smoke propagation. The fire train (a passenger train) is shown in red, the other trains (a passenger on the right and a freight train on the left) in blue.

The resulting self-rescue history is presented in Figure 10. In this particular case it is assumed that the number of persons on the train is small, and no queuing of persons needs to be accounted for. 10 trajectories are generated at 5 locations along the train length, assuming that the 2 persons at each location generally select different escape direction, if possible. The first persons leave the train 1 min after train stop. A second wave is released 2 min later at the same locations, simulating the last persons to leave the train.

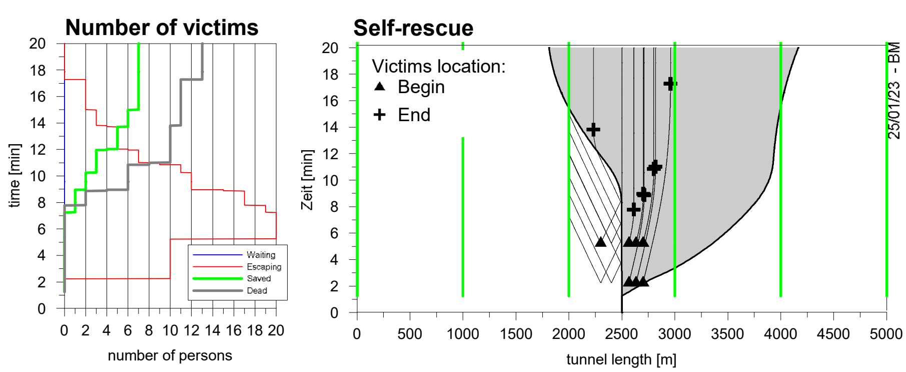

Figure 10. Person position in time (right) and self-rescue evolution (left) – Emergency exits ever 1000 m.

Due to the initial dominating smoke-propagation patterns, the persons on the right-hand side of the fire are trapped in the fire from the beginning. None of them decides to escape towards the fire, to the left. Their chances for self-rescue are not favorable. Much better conditions apply for the persons on the left-hand side of the fire. The ones escaping to the left reach an emergency exit before they are endangered by smoke reversal. The ones escaping to the right see the smoke and reverse their escape direction. The loss of time results in reduced self-rescue chances. The persons waiting, escaping, saved of incapacitated on the left-hand side of Figure 10. The persons are counted in terms of groups, one unit corresponds to persons leaving the train in one direction at any time step. In the present case the total number is 5 locations x 2 escape directions x 2 time steps = 20 units.

Barometric portal pressure differences can have a significant impact even for this comparatively long tunnel. The same scenario, but with a barometric overpressure of 30 Pa at the right portal, is shown in Figure 11. A more rapid reversal of smoke propagation occurs. This results in improved self-rescue conditions on the right at the cost of less favorable conditions on the left.

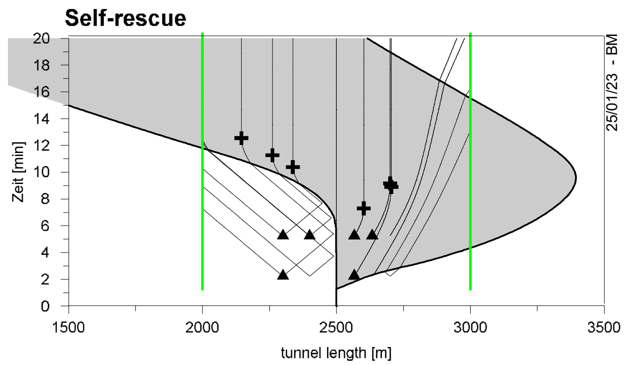

Figure 11. Smoke propagation and self-rescue pattern for the scenario presented in Figure 9 but with 30 Pa barometric pressure difference at the right portal – Emergency exits every 1000 m.

3.3 *Modified train schedule*

A modified setup is investigated in Figure 12. The crossing train enters the tunnel 1 min after the fire train with 120 km/h. As shown in Figure 12, this train can't be stopped and crosses the fire train short after its stop. In this case this train is slowed down only after crossing and leaves the tunnel at 30 km/h. The resulting air velocity and smoke-propagation pattern is shown in Figure 12.

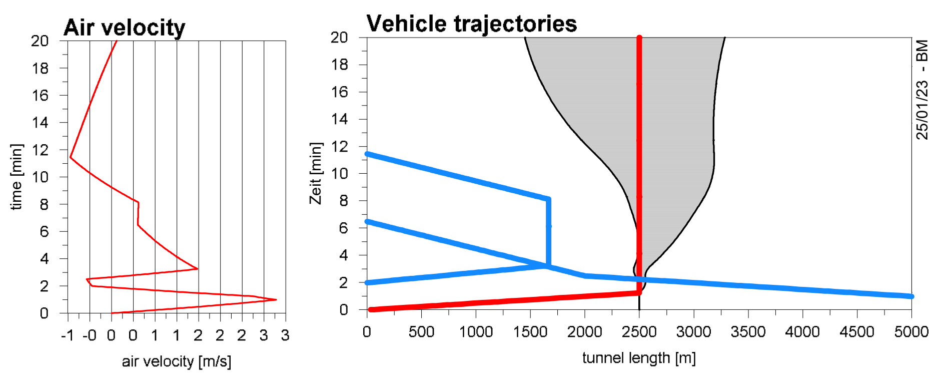

Figure 12. Train motion, longitudinal air velocity and smoke propagation. The fire train (a passenger train) is shown in red, the other trains (a passenger on the right and a freight train on the left) in blue.

The resulting self-rescue patterns, Figure 13, show that conditions for self-rescue are not acceptable. The initial flow propagation in one direction, coupled with a rapid flow reversal, results in unfavorable self-rescue conditions on both sides of the fire. Clear benefits are achieved reducing the distance between the emergency exits, as shown in Figure 14.

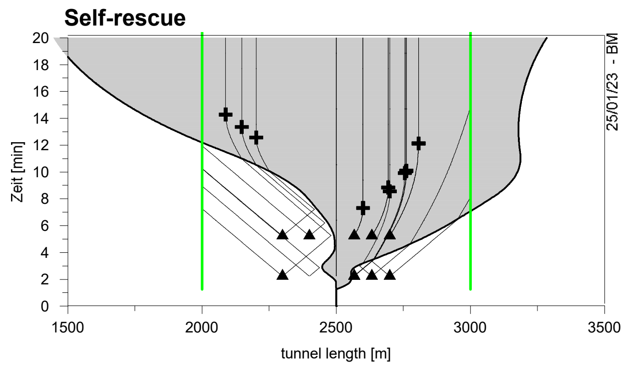

Figure 13. Smoke propagation and self-rescue pattern for the scenario presented in Figure 12 – Emergency exits every 1000 m.

The results of the analysis for these comparatively simple scenarios clearly show, that the accepted distances between the emergency exits (in Europe generally 1000 m for single-tube tunnels and 500 for double-tube tunnels) are frequently excessive. Much better results are achieved using values around 300-350 m, which represent the de-facto standard for the large Alpine tunnels.

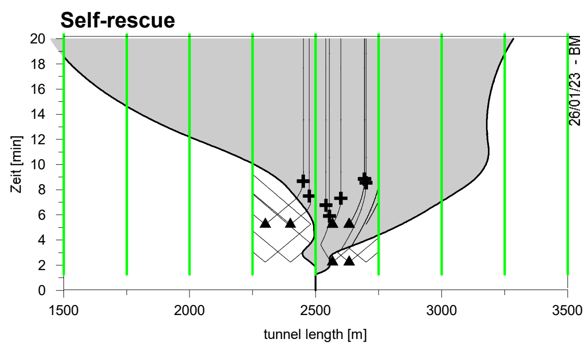

Figure 14. Smoke propagation and self-rescue pattern for the scenario presented in Figure 12 – Emergency exits every 250 m.

4 CONCLUSIONS AND OUTLOOK

Simulation of self-rescue scenarios represents a key element of risk analysis. Modern approaches allow for a very realistic simulation of person motion also in complex configuration. The comprehensive 1D simulation of complete fire scenarios including self-rescue provides direct evidence of the safety level of the infrastructure considered. The results provide direct insight into possible safety issues and immediate guidance for enhancements.

The results clearly show the importance of selecting an appropriate combination of self-rescue facilities and ventilation system. This is particularly important in case of unfavorable conditions, such as frequent congestion of high longitudinal tunnel slope.

A further important finding is that the minimum normative requirements on emergency exits generally used for designing rail and road tunnels lead in several cases to unsatisfactory results. A critical verification of the minimum requirements represents a key element of safety design, which should be mandatory for each design task.

5 REFERENCES

Bettelini, M. 2011. Coupled One-Dimensional Simulation of Smoke Propagation and Evacuation in Road Tunnels” AFTES Int. Congress 2011, 17-19 October 2011, Lyon, France.

Bettelini, M. 2023. Self-Rescue in Traffic Tunnels – Simulation Method. WTC 2023, 12 – 18 May 2023, Athens – Greece.