# Self-Rescue in Traffic Tunnels - Simulation Method

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ABSTRACT: Self-rescue represents the most important and critical safety element in case of fire in underground traffic infrastructures. Ideally, all persons should vacate the underground space immediately after fire onset without leaving their vehicles. In case of self-recue on foot, through the tunnel portals or through emergency exits, they will move in a hostile environment and will be exposed to several risks. The primary requirements for successful self-rescue are the availability of emergency exits, an appropriate smoke-management system and specific, rapid information. These elements must be properly accounted for at design stage. Advanced simulation techniques provide excellent tools for analysis and design. This paper focuses on the combined simulation of fire scenarios, traffic management, smoke propagation and self-rescue in underground traffic infrastructure.

## 1 INTRODUCTION AND OBJECTIVES

An essential safety principle for traffic infrastructures is that all persons involved in an emergency should be able reaching immediately a safe location, ideally the outside, with their own means. This is necessary, because the time required for intervention is frequently long compared with the relevant time scales of fire development and smoke propagation.

Persons escaping on foot in an underground infrastructure are exposed to a number of severe threats due to vehicles, heat, smoke and toxic combustion products and many more. Vehicles not directly affected by the fire should leave the tunnel or should be prevented from entering the tunnel. This is associated in particular to fire detection and traffic management. Such important aspects shall not be discussed herein.

This paper focuses on self-rescue of tunnel users in case of emergency and more specifically on its simulation. It is assumed that vehicles are blocked inside the infrastructure and self-rescue occurs on foot within the tunnel. This is the case e.g. for all vehicles trapped in a traffic jam or blocked by the fire in road tunnel. In the case of rail and metro system, we shall primarily focus on the fire train. During self-rescue, persons must leave their cars and trains and escape on foot. They are exposed to an unknown, hostile, environment and shall reach as rapidly as possible a safe location. For the purposes of the present paper, it is not necessary distinguishing between final escape to the outside or to underground protected locations, such as parallel tunnel tubes or shelters. We shall simply assume that self-rescue leads to an adequately protected location.

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.

Several technical mitigating measures play an essential role for the outcome of self-rescue. In the present context, they shall be accounted for but not handled in a systematic manner. Conversely, user information and ventilation require a specific treatment since they directly impact the simulation and outcome of self-rescue.

## 2 SELF-RESCUE

The literature on self-rescue and human behavior in emergency situations is ample and is consolidated in a number of excellent general references, e.g. NFPA's Fire Protection Handbook and the SFPE Handbook of Fire Protection Engineering. This discussion shall focus on the aspects, which are most relevant from the point of view of analysis and simulation.

In general terms, the relevant stages of self-rescue are as follows (PIARC, Road Tunnels Manual): "A closer look into the self-rescue process reveals that the evacuation behavior of people can be divided into several phases. At the beginning is the pre-evacuation phase, which includes all events before the start of the evacuation and ends with the decision to escape. In the subsequent evacuation phase, we can distinguish the pre-movement phase and the movement phase. During the pre-movement phase, the tunnel user searches for information and selects an escape route. The movement phase includes all behavior that tunnel users display during the evacuation until they reach an escape target."

Empiric research shows that the length of the pre-evacuation phase, before reaching the decision to escape, can be long and decisive for the outcome of self-rescue. This delay (which can last as long as the escape phase itself, if no proper alerting is provided) depends very much on contingent situations and is essentially impossible to predict. The safety engineer shall rather focus on active measures for reducing it. Proper user information and communications plays here a central role. On-board information systems on rail vehicles can be very effective for minimizing time loss before evacuation. Radio broadcast and public address systems, possibly integrated by optic and acoustic signals, play an essential role, and are successfully used in road tunnels.

The movement phase is particularly important and delicate. The escaping persons seek for the best way for reaching a protected area in an unknown and hostile environment, where smoke could represent a major threat. Appropriate guidance and sufficient visibility conditions are essential prerequisites for successful self-rescue. Ventilation plays a fundamental role for enabling tenable conditions during the whole self-rescue process.

Self-rescue can be assessed in terms of (Shields, 2012; SFPE Handbook)

- Required Safe Egress Time (RSET, the time between ignition and complete evacuation) and
- Available Safe Egress Time (ASET, the time between ignition and the onset of untenable conditions),

and the safety objective can be formulated as

$$\text{RSET} \ll \text{ASET}$$

From a computational point of view, the required time RSET can be expressed as follows (SPE Handbook):

$$\text{RSET} = t_d + t_a + t_o + t_i + t_e$$

with

$t_d$ = time from fire ignition to detection
$t_a$ = time from detection to notification of occupants of a fire emergency
$t_o$ = time from notification until occupants decide to take action
$t_i$ = time from decision to take action until evacuation commences
$t_e$ = time from the start util the evacuation in completed

Its value depends on several factors, including number and location of emergency exits, number of persons and person behavior (see e.g. Noizet (2012) and UPTUN (2008)). The RSET can be reduced by means of appropriate technical measures, including user information, signing, lighting etc. Important issues related to persons with reduced mobility shall not be addressed herein.

The available time ASET depends on fire growth and development as well as on smoke behavior and smoke-management measures. This can be actively influenced by technical measures such as fire ventilation and FFFS. According to NFPA 130, a tenable environment is defined as "an environment that permits the self-rescue or survival of occupants". NFPA 130 specified the following tenability conditions:

- Smoke obscuration and visibility conditions: Min. 30 m for internally illuminated signs and min. 10 m for walls and doors or externally illuminated signs
- Heat effects: Exposure temperature ≤ 60°C for 10 min and radiant heat exposure ≤ 2.5 $kW/m^2$
- Carbon monoxide: FED < 0.3 (FED = Fractional Equivalent Dose)
- Air velocity ≤ 11 m/s

Practical experience shows that in tunnel environments tenability conditions are mostly limited by visibility. A visibility level lower than 10-20 m at 2-2.5 m over the escape paths is generally critical.

The concept of panic is particularly important in the perspective of self-rescue management and analysis. Schultz (1968) defined panic as "A fear-induced flight behavior, which is nonrational, nonadaptive, and nonsocial, which serves to reduce the escape possibilities of the group as a whole". As such, person behavior in case of panic irrational and unpredictable and cannot be simulated. However, there is sufficient evidence that panic is a rare phenomenon. "Panic is very rare even in fires. Normal patterns of behavior, movement route choices, and relationships with others tend to persist during emergency situations" (SFPE Handbook). Similarly, UPTUN (2008) concludes that "the preliminary phase is characterized by insecurity, misinterpretations, indecisiveness, and information searching in order the existence of the fire to be confirmed. Although psychological conditions like stress and anxiety deteriorate people's ability to comprehend and solve problem, they rarely lead to panic and irrational actions." However, according to UPTUN (2008), "in a serious situation panic behavior arises when people fear that they cannot escape". This remark obviously has far-reaching implications for safety design and operation.

## 3 SIMULATION OF SELF-RESCUE

### 3.1 *Objectives and levels of simulation*

Simulations of fire scenarios are generally carried out for design or for design-verification purposes. A special application is the assessment of consequences for QRA (Quantitative Risk Analysis). A key objective at design stage is design optimization, particularly in terms of self-rescue (egress routes and emergency exits) and ventilation (ventilation design and ventilation control). Both ventilation and escape routes are cost-intensive components, which should be optimized jointly. In fact, the primary objective of ventilation is keeping the egress routes free of smoke during the entire self-rescue process. The analysis required in the framework of safety analysis is carried out along similar lines, but generally cope with an existing safety design and point at the assessment of residual risks, particularly in terms of number of victims.

Several levels of simulation can be used for different purposes. In simple cases, global approaches along e.g. the lines defined by NFPA 130 can be sufficient. They rely on empirical data and require a very limited amount of computation. The results can be assessed directly based on specific criteria, such as the ones stated in NFPA 130 for underground rail stations:

- There shall be sufficient egress capacity to evacuate the platform occupant load from the station platform in 4 minutes or less.
- The station shall be designed to permit evacuation from the most remote point on the platform to a point of safety in 6 minutes or less.

On the other end of the complexity spectrum, comprehensive approaches based on CFD and detailed simulation of person motion provide very detailed information for assessing RSET and ASET in a very accurate manner. From the point of view of person motion, one can roughly distinguish between "macroscopic" (fluid dynamic) and "microscopic", individual models. The former treats the flow of persons as a fluid, the latter accounts for every individual person, with specific characteristics and moving pattern. "Microscopic" approaches provide particularly realistic results, at the expense of an increased modeling effort.

The simplest approaches provide only limited insight into the self-rescue process. They can point at weaknesses of the safety system, but generally deliver little guidance for improving design. Comprehensive approaches deliver a great detail and insight on person motion and smoke propagation but are generally too expensive for general use at design stage. This kind of analysis is frequently limited to the most representative scenarios and to limited parameter variations.

One-Dimensional (1D) simulation represents a very powerful and appealing approach both at design and design-verification stage. It offers a number of distinct advantages compared to other approaches:

- Capability of analyzing full fire scenarios in a comprehensive manner, including e.g. dynamic traffic behavior, ventilation control, meteorologic and thermal conditions
- Possibility of testing different ventilation systems and smoke-management scenarios
- Easy variation of number and location of emergency exits
- Coupling of person motion during self-rescue with all relevant tunnel and traffic parameters.

The distinct advantage over 1D simulation is the possibility of investigating in a rapid manner complete scenarios, which include all relevant aspects and effects. The obvious disadvantage is a significant loss of detail, particularly concerning smoke stratification, which can only be assessed in a simplified manner.

### 3.2 *One-dimensional analysis of fire scenarios*

One-Dimensional (1D) simulation allows for the comprehensive analysis of fire scenarios, which accounts for the entire tunnel and for all aspects relevant for person safety at self-rescue stage. This allows e.g. for quick investigation of a wide spectrum of safety concepts, such as the interaction between selection of ventilation system and allowable spacing of emergency exits. This is particularly valuable at early design stages, where the outline of safety design is being developed.

The essential ingredients of 1D simulation models are (for details see Bettelini (2008 & 2011)):

- Detailed geometric characteristics of the entire tunnel, including e.g. variation of slope and cross section
- Environmental and boundary conditions, such as barometric pressure differences, portal wind and natural temperature differences
- Comprehensive models for road-traffic, including fluid and congested traffic and traffic management in case of fire
- Comprehensive models for train motion (specification of the different train types involved, schedule and train-management in case of fire)
- Implementation of all relevant normal and fire-ventilation models (natural ventilation, longitudinal ventilation, semi- and fully transverse ventilation, hybrid ventilation systems)
- Implementation of detailed ventilation-control procedures, such as PI controllers for ventilation control, allowing for a precise reproduction of the ventilation-control routines implemented in a tunnel
- Fire onset, intensity, and time development
- Models for smoke propagation and stratification
- Models for person motion, including smoke interaction and the effects of temperature and gas exposure.

The present discussion partly relates to the Author's own 1D simulation tool TunSim, a powerful and versatile 1D simulation tool for the analysis of rail and road tunnel fire scenarios. The code evolved over the last 20+ years and was applied worldwide. All examples presented herein were computed using version 4.8 of TunSim. The physical models and code validation were presented in Bettelini (2008 & 2011).

Typical, powerful applications of 1D simulation at design stages focus on ventilation design and optimization and emergency exits. Ventilation and emergency exits are two intrinsically interdependent elements of the safety chain. An appropriate tradeoff between these cost-intensive elements can have very beneficial impacts on both safety and construction cost, particularly in the case of existing tunnels. Typical applications at design stage include:

- Selection of ventilation system for new road tunnels (e.g. natural ventilation vs. longitudinal ventilation, longitudinal ventilation vs. complex ventilation system with smoke extraction, semi-transverse vs. transverse ventilation)
- Verification, if safe rail-tunnel operation is allowable with natural ventilation
- Determination of the allowable spacing of emergency exits, e.g. in case of road tunnels with significant longitudinal slope and bidirectional traffic
- Optimization of ventilation-control procedures.

The focus at design-verification stage is on the verification of the safety level, which can be achieved in an existing or fully designed rail or road tunnel. Representative fire scenarios are analyzed in detail with the main objective of verifying if a fair chance of self-rescue can be provided to the users in the tunnel. Detailed scenario analysis represents, jointly with QRA, a key component of the safety verification process. While QRA provides global information on the overall safety level, the analysis of representative fire scenarios allows assessing the need for additional safety measures and a precise evaluation of the residual risks.

Finally, 1D analysis is frequently a key element of QRA. Its flexibility and relative simplicity allow for the rapid simulation of a very large number of scenarios, which are needed for a representative quantification of the consequences in terms of number of victims. 3D simulation delivers significantly more detailed and reliable results (particularly in terms of smoke distribution, visibility, thermal and radiant load etc.) but its higher complexity and cost generally leads to severe limitations of the number of scenarios considered and to a loss of representativeness.

### 3.3 *One-dimensional simulation of self-rescue*

*Overview*

The key ingredient of the simulation of self-rescue are:
- Initial location of the escaping persons
- Preparation time, decision and start of self-rescue
- Analysis of the self-rescue process and effect of smoke on the conditions of the escaping persons.

These elements shall be reviewed and illustrated in some detail in the following paragraphs based on the powerful self-rescue engine implemented in TunSim.

*Vehicle motion and location of escaping persons*

The initial location of the escaping persons mostly depends on the position of the vehicles. In the case of road tunnels, the traffic module delivers the position and speed of all vehicles in the tunnel. The typical traffic-management pattern for the comparatively simple case of unidirectional fluid traffic is presented in Figure 1. More complex situations, such as congested or bidirectional traffic, are handled analogously.

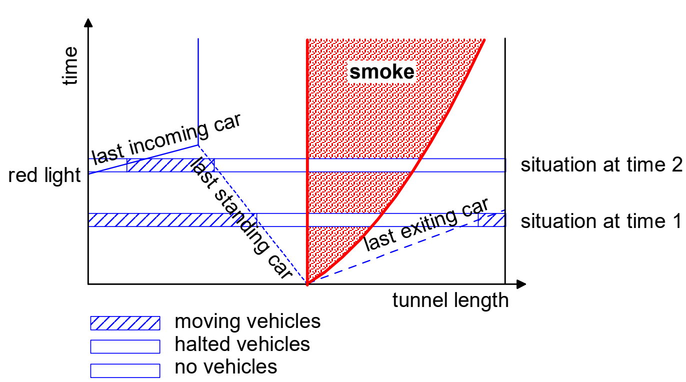


Figure 1. Overview of the traffic model in case of unidirectional fluid traffic.

Rail tunnels are significantly simpler from this point of view. Starting from the relevant train schedule, train management in case of fire can be specified exactly as foreseen in the emergency planning procedures. This includes trains not directly involved in the fire leaving the tunnel. All trains, which already passed the fire location leave the tunnel, generally at reduced speed, for preventing excessive perturbations of the aerodynamic conditions in the tunnel. Crossing or following trains shall generally be stopped and leave the tunnel in reverse direction. If this is not possible, trains shall be evacuated in the tunnel or in a rescue station.

*Selection of escape direction*

This is a fundamental step, with a large impact on the outcome of the process. Each person in the tunnel will individually select its escape direction based primarily on its location, fire location, distance from emergency exits, smoke conditions etc. The available amount of information varies depending on individual location and time. As an example, users in the immediate vicinity of the fire might see it and include this information in their decision process. At larger distances, the information available on the fire is much more limited. Before detection and alert to the users, there might be no awareness of the emergency situation. It is therefore essential, that only the information available at a specific location and time is included in the simulation process.

Generally, information on distances to the nearest emergency exits in both directions are provided at regular intervals in a tunnel. Less frequently, the escape direction is prescribed by means of fixed or dynamic signing. This information could be supplemented by other optical devices, such a flashing lights, and voice messages, provided through public-address systems and/or direct passenger information to all persons on a train. Escape signage or any other kind of guidance could be unavailable in older tunnels.

Depending on conditions and circumstances, several basic deterministic strategies for the individual selection of escape direction should be considered:

- Shortest escape distance
- Escape towards the left portal
- Escape towards the right portal
- Escape away from the fire.

The selection of the most appropriate strategy for modeling self-rescue in any given case depends primarily on tunnel characteristics, traffic type and conditions, fire location, available user information, signing and guidance etc. As in real life, the general strategy might change under specific circumstances. The following elements are accounted for by TunSim:

- Different strategies apply in the vicinity of the fire, where the fire is visible and directly impacts the decision. Therefore, TunSim allows for the specification of different self-rescue strategy at different distances from the fire.
- Users reached by the smoke front will generally escape in the opposite direction, unless an emergency exit is located in their immediate vicinity. The arrival of the smoke front can also trigger the reversal of escape direction.
- Large fires will prevent accessing emergency exits located in their immediate vicinity. There is therefore a possibility of blocking emergency exits within a given distance from the fire as soon as the fire heat-release rate exceeds a given threshold.
- Persons located in the immediate vicinity of an emergency exit will generally select it as escape goal, independently of the prescribed strategy, unless it is blocked by fire.

There are situations, where different persons at the same location and under identical conditions might select different escape directions. This possible scatter of individual decisions can be mimicked through a random choice between a primary and a secondary self-rescue strategy. In this case, the percentage of persons randomly selecting the secondary strategy can be specified. This stochastic variability will lead to some variability in the outcome of self-rescue, in spite of identical scenario definitions. This is undoubtedly an omnipresent component emergency management in real life.

*Preparation time and start of self-rescue*

Experience shows that the time interval between fire inception and start of self-rescue can vary within a significant range, depending on conditions. There is also a large variability for persons involved in the same fire incident, depending on fire and person location, but also on individual differences. The complexity of the individual decision process can only be accounted in a simplified manner in the simulation process. The following elements are included in the simulation with TunSim as potential triggers for the individual inception of self-rescue, with appropriate time delays and, where appropriate, distances (the relevant parameters are specified for each element):

- Fire detection and alarm to the users (time delay after alarm)
- Vicinity of the fire (time delay vs. fire distance)
- Vicinity of the smoke front (distance and time delay)
- Interaction with escaping persons (distance and time delay)

Self-rescue is initiated as soon as one of the criteria is satisfied and the corresponding time delay is expired. The influence of escaping persons on the whole self-rescue process is particularly important. It was shown by empirical research (Norén & Winér, 2003), that the example from fellow tunnel users has a powerful triggering effect on self-rescue (“herd effect”). For this reason, approaching escaping persons can trigger self-rescue, with a specified delay.

*Analysis of the self-rescue process*

Self-rescue starts individually. Its evolution in time is simulated in a step-by-step manner and is coupled with fire development and smoke propagation. The escape velocity for persons not affected by smoke inhalation or cumulated thermal loads depends primarily on visibility conditions. Figure 2 illustrates the decay of escape velocity with increasing smoke concentration for irritant and nonirritant smoke.

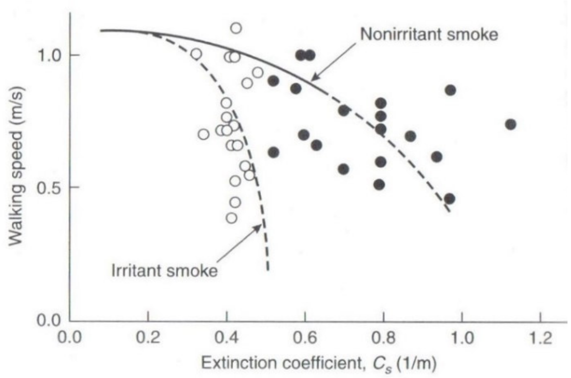


Figure 2. Walkins speed in smoke (SFPE Handbook).

In case of escape in partially or completely destratified smoke, smoke exposition results in a decay of physical conditions and a reduced escape velocity. This eventually leads to full incapacitation unless an emergency exit can be reaches in time. The simulation of individual escape histories is stopped as an emergency exit is reached or at full incapacitation.

Criteria for reversal of escape direction are implemented for cases, where escaping persons are reached by the smoke front. In such conditions, the most appropriate escape direction is reevaluated individually, based on the location of the nearest emergency exit and the propagation direction of the smoke front.

*Smoke stratification, visibility and pollutant concentration*

Smoke stratification has both direct and indirect impacts on individual self-rescue histories. Visibility conditions directly impact escape velocity, as discussed on the previous section. Additionally, the stratification level affects thermal conditions and pollutant concentration. The cumulated effect of this exposure affects the conditions of the persons escaping in the smoke and further decreases their escape velocity.

Smoke stratification is an intrinsically 3D phenomenon, which cannot be properly assessed by means of 1D simulation. A simplified concept is used in TunSim, based on the following parameters:

- Longitudinal air velocity (high values reduce stratification)
- Distance from fire (stratification tends to decrease at larger distances from the fire herd)
- Temperature increase inside the smoke layer

– Vicinity to activated jet fans, which have a strong destratifying effect on a smoke layer.

A parameter range for partial or full destratification is specified for each parameter, considering different levels of overall disturbances (high, intermediate and low).

Based on these parameters, the level of smoke stratification is evaluated at each time step and location in tunnel. This allows assessing the local visibility, thermal impact (temperature and radiative load) and smoke concentration (irritant and asphyxiant gases).

*Person conditions and incapacitation*

Exposition to heat and smoke leads to a deterioration of the physical conditions of the escaping persons. The following parameters are relevant:

- Thermal conditions (temperature and radiation)
- Concentration of asphyxiant gases
- Concentration of irritant gases.

The evaluation of individual exposure to radiant and convective heat and inhalation of asphyxiant gases is based on the concept of fractional effective dose FED. Exposition to irritant gases is evaluated based on the concept of fractional effective concentration FEC. The analysis is based on the concepts and principles exposed in ISO 13571, SFPE Handbook and PIARC (1999).

## 4 CONCLUSIONS AND OUTLOOK

Simulation of self-rescue scenarios represents a key ingredient 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. Its distinct advantage over other approaches is an excellent balance between simulation complexity and result quality. The results provide direct insight into possible safety issues and immediate guidance for enhancements.

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