A new tunnel assessment procedure integrating smoke dispersion and evacuation models

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A NEW TUNNEL RISK ASSESSMENT PROCEDURE INTEGRATING SMOKE DISPERSION AND EVACUATION MODELS

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ABSTRACT

This paper focuses on a new risk assessment procedure for tunnel. This procedure is based on the coupling between smoke dispersion models and evacuation models. It has been developed inside the UPGRADE procedure put in place in the UPTUN project. The method is based on two heat and mass flow (HMF) models for the calculation of tenability conditions due to a fire event: NewVendis® for the 1D calculation and the global equilibrium of the tunnel network and FASIT® for the calculation in the vicinity of the fire. Tenability conditions are used as input data for the evacuation calculation carried out by the evacuation model CRISP®. All results (smoke dispersion and evacuation) are then combined in tenability diagrams which are a superposition of HMF tenability conditions and users' location in the tunnel. This kind of presentation can then be used to help understand injuries or people casualties and to take efficient safety measures to increase safety level in tunnel.

KEYWORDS: *Tunnel, Fire, Risk assessment, Smoke dispersion, Evacuation, Computer model, Tenability, HVAC*

INTRODUCTION

Because tunnels are complex systems with many interactions between ventilation equipment, atmospheric conditions, operators' and user's behaviour, it is often difficult to make a good evaluation of the tunnel safety level. Nevertheless, over the last few years, authorities, tunnel operators and designers have become aware of the necessity to consider all parameters such as traffic, users, management and tunnel equipment, which could affect tunnel safety .

In this context, the Commission emphasises the need to consider a European Directive on harmonisation of minimum safety standards to guarantee a high level of safety for the users of tunnels, particularly those in the Trans-European Transport Network. The UPTUN project fits in the European Directive and is a good way to reach the goal of safety in tunnels.

The work package 5 of UPTUN consists of developing an UPGRADE procedure for the holistic evaluation of fire safety level and upgrading of an existing tunnel. At the heart of the procedure is a risk assessment model that provides the risk profile based on the safety features of the tunnel under investigation. There are two levels of risk assessment:

(i) calculation of smoke conditions at different positions and times within the tunnel, calculation of the toxic dose absorbed by people as they escape, and examination of the results. For the UPTUN project, the smoke movement was calculated by the models New Vendis and FASIT, and the human response by the model CRISP. Examination of the results entails superimposing the tracks $\underline{\mathbf{x}}(t)$, made by individual people, on tenability diagrams of smoke conditions as a function of $\underline{\mathbf{x}}$ and t. The tenability diagrams were generated by New-Vendis.

(ii) Monte-Carlo simulation, using a fully-integrated smoke movement and evacuation model (CRISP) to examine the consequences of different fire sizes, locations within the tunnel, numbers of people, etc. The outputs of this model give probability distributions, for example the numbers of people dying given that a fire has occurred. The model can take account of the effects of early detection and warning systems, suppression systems, or the provision of emergency exits in addition to the tunnel portals. By running simulations with different safety systems in place, the expected benefits (risk reductions) can be calculated directly from the model outputs, and used to help determine the most cost-effective approaches to adopt for a particular tunnel.

This paper presents details of the first of these two levels of assessment. The next section gives a short description of the models used. This is followed by a section covering the global calculation procedure and data exchange between models.

At this stage an overview of data exchanges procedure is described between New-Vendis for the global calculation of smoke dispersion in the entire tunnel, the software FASIT which refines the calculation in the vicinity of the fire, and the evacuation model CRISP. Other models which perform similar functions could be substituted if desired. The main objective of the procedure is the building of human tenability diagrams presented as a superposition of HMF tenability conditions and users' displacement in the tunnel during the evacuation phase.

QUICK DESCRITPION OF THE MODELS USED IN THE PROCEDURE

Smoke dispersion models : NewVendis and FASIT

The procedure is based on two different smoke dispersion models or also called Heat and Mass Flow Models (HMFM) for the evaluation of the tenability conditions in the tunnel. These models are described hereafter

1D model : NewVendis®

NewVendis is a one-dimensional numerical code and is clearly the key to improved evaluation of accidental effects in confined location such as subway networks, tunnels and storage galleries. The effects are due to the presence of an accidental source like a fire and to the influence of a general ventilation system [1-2].

The modeling of the tunnel takes into account all of the physical effects likely to influence the behavior of this network. These influencing parameters vary over time so as to obtain data on network dynamics and on accidental effects which are, by essence, transitory.

The tunnel network is described in NewVendis by a set of galleries. Each gallery is characterised by its curvilinear length, its area and its hydraulic diameter. Internal points are then added in the gallery to refine the grid and calculate more accurately the smoke dispersion. Galleries are connected each other as a set of branches as it is shown on Fig. 1.

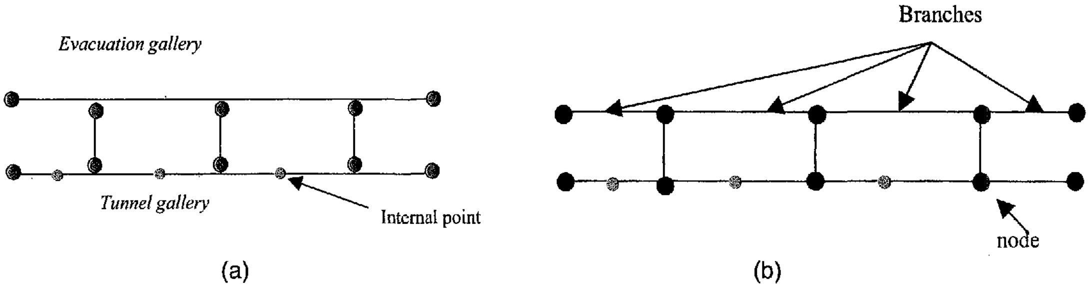


Fig. 1: tunnel network representation in NewVendis – Before connection (a) – After connection (b)

Transient velocities in the network are calculated on the basis of pressure effects that can be introduced in the models. These effects are:

- pressure loss,
- natural atmospheric conditions,
- ventilation systems,
- piston effects due to traffic...

The calculation of the aeraulic equilibrium of the tunnel network consists of the resolution of pressure and mass flow rate with the Hardy-Cross algorithm [3].

The heat and pollutant mass transfer calculation is based on a diffusion model. Each species is driven inside the tunnel network with the same velocities as those calculated in the entire network with the Hardy-Cross algorithm.

3 layer zone model : FASIT®

In FASIT [4], the tunnel is represented as a series of zones, each at ambient temperature and flow conditions. The zone positions and lengths are either input by the user or set automatically with an exponential increase with the distance from the fire (see.Fig. 2).

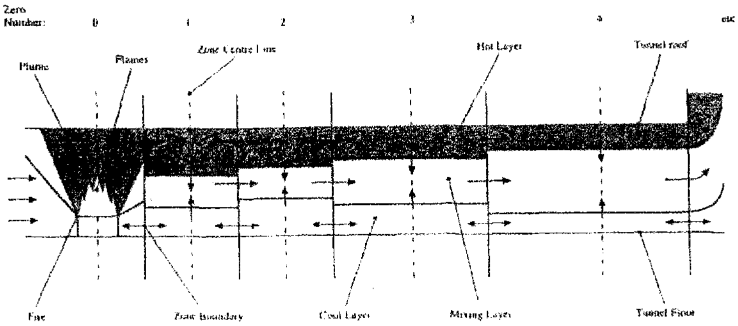


Fig. 2 : Tunnel zone / layer schematic

At various times and for varying intervals, the movement of smoke and heat from the fire is predicted using a three-layer model. Analysis of tunnel fire experimental temperature and velocity data indicated that three layers gave a good representation. The layers can be described as hot, mixing, and cool and have three associated wall "layers". Thus, the tunnel fire conditions are predicted on a multi-zone, multi-layer domain. The user specifies the fire heat output and mass flow, and FASIT predicts the temperature, the velocity, the depth and concentration in each layer for each zone throughout the tunnel.

EVACUATION MODEL: CRISP®

The CRISP model (Computation of Risk Indices by Simulation Procedures) is a Monte-Carlo simulation for fire risk assessment [5-9]. It was originally developed to model fires in buildings, but has been adapted for tunnels. The scope of the model is intended to cover the entire fire scenario. The sub-models represent physical 'objects' include tunnel segments (corresponding to the zones used for the smoke movement calculations), escape passages, doors, detectors and alarms, suppression systems, vehicles (fuel packages), hot and cold smoke layers, and people. The randomised aspects include starting conditions such as the number, type (behaviour and other characteristics) and location of people within the building, the location of the fire and type of burning item (car, HGV, rail coach, etc).

CRISP incorporates a detailed behaviour model, rather than something simpler which would run faster. The justification for this is that the risk assessment is based on fractional effective dose (FED) and accurate FED estimates require accurate exposure times. Therefore the behaviour model needs to predict where people will go, and how long they will spend in different areas (rooms) of the building. In a tunnel, the FED calculations would need to know how long people spent in different positions in the tunnel, relative to the fire location.

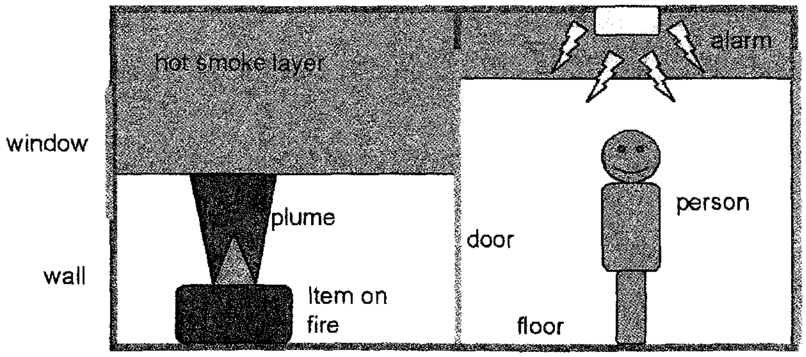


Fig. 3 : schematic representation of some of the different object types within the CRISP model (this is the version for a building, although the tunnel version is very similar).

DESCRIPTION OF THE PROCEDURE

Global flowchart of the procedure

The main goal of the risk assessment procedure developed by INERIS in collaboration with BRE is the coupling of the different models described above in order to build human tenability diagrams. This concept can be represented through the flowchart on Fig. 4. This flowchart describes the different steps and links towards the prediction of consequences that will be experienced by tunnel users during evacuation in the event of a fire. First, a fire scenario established by an intelligent system describes the fire event. The heart of this intelligent system is a database, which collect all information about the tunnel: geometry, safety features, traffic data... By this way, all parameters describing the fire scenario are collected through this database.

The first link of the procedure (1) is the connection between the intelligent system INTELLITUN and the model NewVendis. This connection provides the geometry characteristics of the tunnel, the ventilation system, traffic information and design fire scenario. Other links are more specific. Their description is given in the following paragraph.

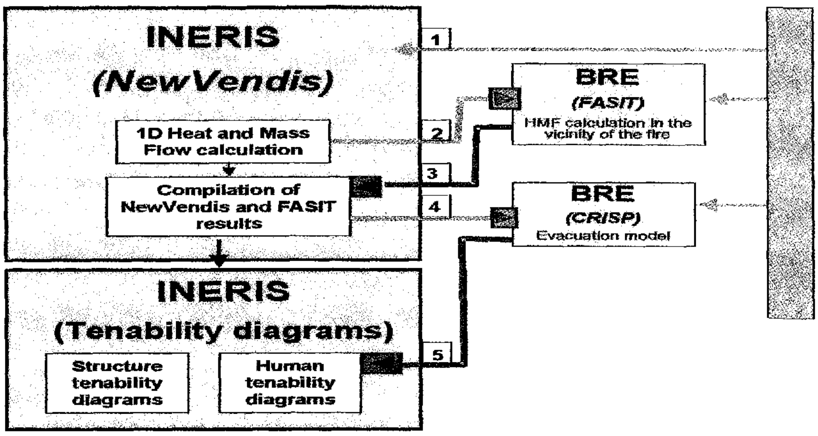


Fig. 4 : Flowchart of the risk assessment procedure

DESCRIPTION OF THE COUPLING LINKS

Coupling between 1D model NewVendis and zone model FASIT : link (2) and (3)

The coupling between the two dispersion models is strongly dependent on the two geometrical approaches. The first step is the calculation of the global heat and smoke dispersion in the entire network of the tunnel. This calculation, made by NewVendis on a 1D geometrical base, is particularly adapted to estimate the response time of the global tunnel system, which can not be done with refinement models such as zone models or CFD models. This calculation provides detailed information of transient gas velocity influenced not only by traffic scenario during the first minutes of the fire event, but also by the ventilation system a few minutes after its activation.

Nevertheless, this model does not take buoyancy effects into account. By this way, smoke stratification in the vicinity of the fire is not modeled. The calculation of tenability condition is then refined with the FASIT zone model. To do this, a refinement zone is first determined after NewVendis calculation. This zone corresponds to the estimated stratified zone. Then, NewVendis provides to the model FASIT the following input data:

- geometrical characteristics of the refinement zone,
- transient velocity and gas temperature at flow boundaries of the refinement zone. These transient parameters are those calculated by the 1D model,
- Design fire curves.

After FASIT calculation, smoke dispersion parameters are collected and a combination of HMF properties is established to prepare tenability conditions on evacuation paths. In the non-stratified area, the combination process makes use of 1D calculation from NewVendis. In the stratified area, a selection of results at head height is established from the three layers zone model calculation.

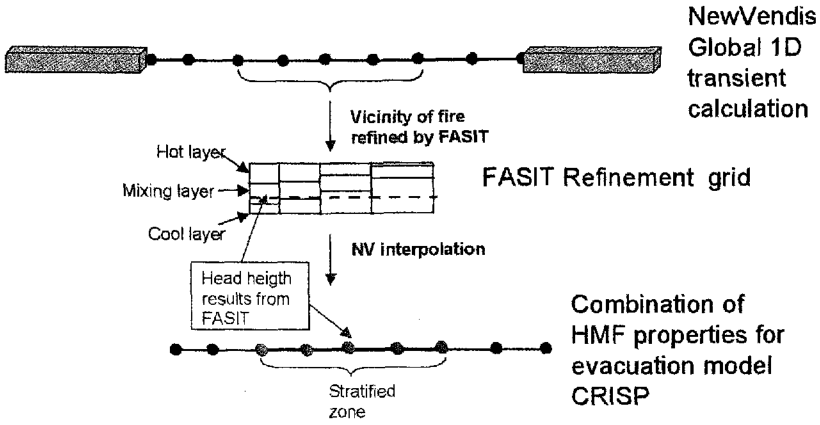


Fig. 5: coupling schematic of smoke dispersion models

Coupling between NewVendis and evacuation model CRISP: link (4) and (5)

The coupling between the dispersion model NewVendis and the evacuation model CRISP is also strongly dependent on geometrical approaches. In NewVendis, the evacuation area is represented by evacuation paths based on the gallery and internal point description. CRISP does not use pre-defined exit paths as described above. Evacuation paths defined in NewVendis are then transformed by a set of connected segment in which users can choose their own exit route (see Fig. 6). Three kinds of information are then provided for the connection between NewVendis and CRISP:

- geometrical information of evacuation area: list of paths and internal points which define segments boundaries for CRISP,
- time variation of heat and mass flow properties for each segment calculated by smoke dispersion models,
- users locations at the beginning of evacuation. These locations depend on traffic scenarios and are calculated by the traffic model implemented in NewVendis.

The simulation of the evacuation scenario also provides three kinds of parameters used by NewVendis for the building of human tenability diagrams. These parameters are (see Fig. 7):

- users' position at each time step,
- users' Overall Fractional Effect Dose (OFED) for each time step.
- Users' Fractional Effect Dose due to carbon monoxide (FED) for each time step.

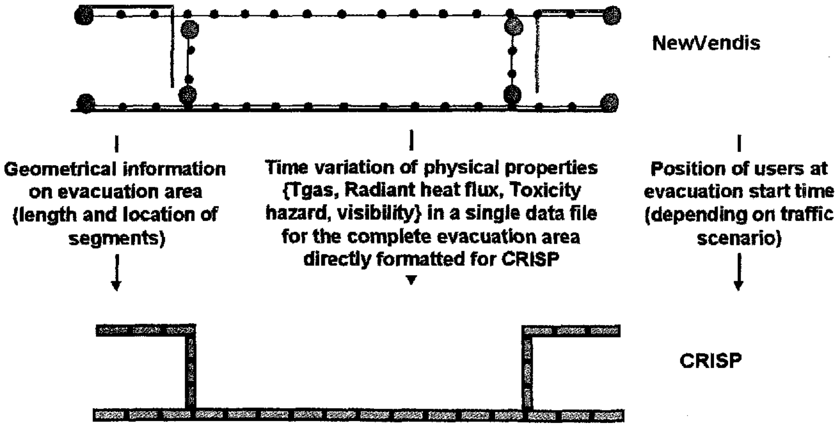


Fig. 6 : Schema of the information transfer from NewVendis to CRISP

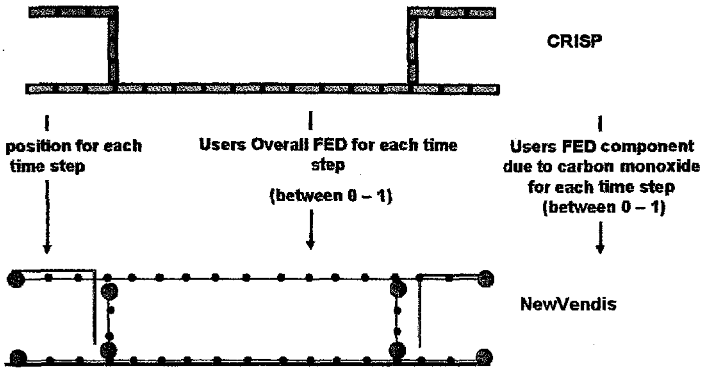


Fig. 7 : Schema of the information transfer from CRISP to NewVendis

APPLICATION TO A BASIC EXAMPLE

Description of the test case

The basic example used to validate the procedure is a 1km bi-directional tunnel. The fire occurs at 250 m from the entry portal. The curve of the design fire heat release rate corresponds to the 100 MW Swiss curves as presented on Fig.8.

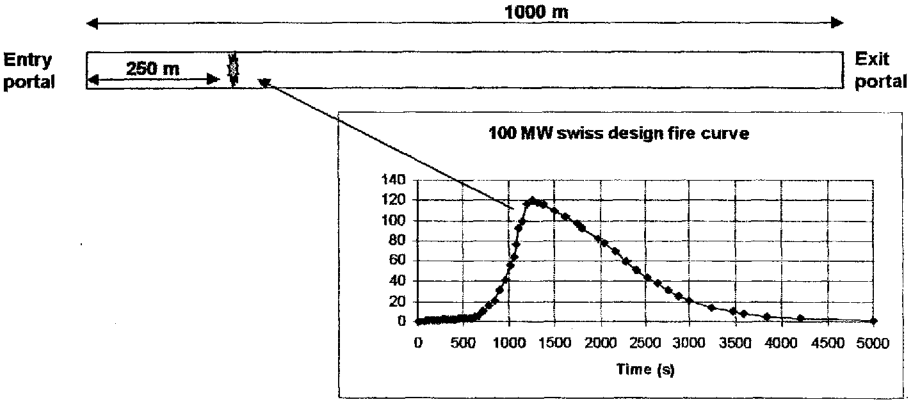


Fig.8 : fire scenario of the basic example

A pressure difference of 15 Pa is applied between portals, which creates a natural longitudinal velocity from entry portal to exit portal. The traffic implemented has a density of 1000 vehicles./h per direction (70% cars, 20% HGV, 10% coaches). The vehicle speed is 70 km/h before fire event. The fire induces a traffic jam in the two directions calculated by the traffic model in NewVendis.

HUMAN TENABILITY DIAGRAMS

The results presented hereafter are based on heat and toxic tenability conditions calculated by the smoke dispersion models. Evacuation scenarios are calculated for four options of evacuation safety features:

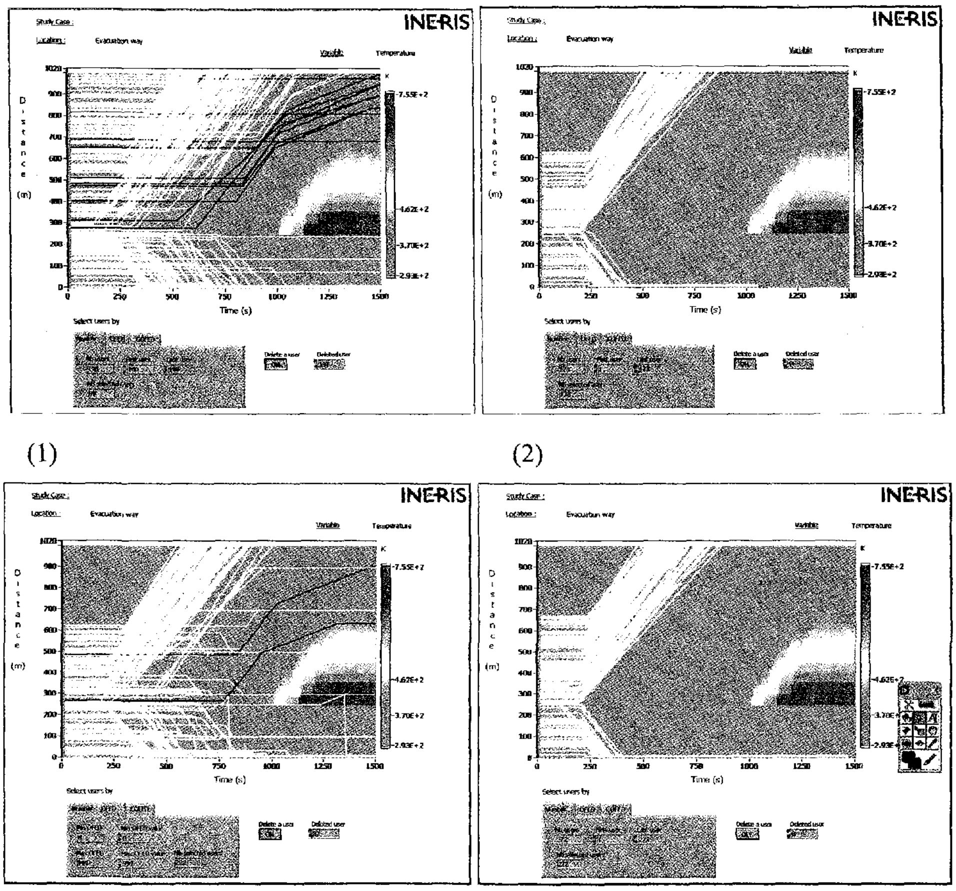
1. no side exit and no detection/alarm : users can evacuate only by tunnel portals. Each user starts to evacuate following her own perception of tenability conditions (drop of visibility conditions for instance),
2. no side exit but detection/alarm : users start evacuation at the same time due to alarm signal,
3. side exits and no detection/alarm : users can evacuate by tunnel portals and by safety exits integrated in the side of the tunnel every 200 m,
4. side exits and detection/alarm.

Human tenability diagrams are presented in Fig. 9. Blank lines correspond to the trajectories of safe users (also including injured person), black lines show the trajectory of persons who die during evacuation.

These results show that in the first option (1), nine people downstream the fire die. The reason is due to the period of the time passed when they decide to start their own evacuation. This period is influenced by their own perception of the bad temperature conditions. When they start to evacuate, they can not pass through the fire because the temperature is too high. The only possibility to exit is to walk toward the exit portal but this part of the tunnel is rapidly covered by hot smoke because of the longitudinal velocity from entry portal to exit portal.

The results with side exits (3) shows that the number of death is considerably reduced. Only two persons die. Some people enter in the refuges when they reach too bad temperature conditions. But this safety equipment is not sufficient because in this case, the behaviour of people who die shows that they decide to not take refuges probably due to an under estimation of the bad conditions.

The two case with detection and alarm (2) and (4) show that nobody die. It is also interesting to underline that people are using the portal from preference for the case with side exits (4). Indeed, the early warning from the alarm gives them enough of a start that they do not feel so threatened from the smoke that they have to change plans and use a side exit.



(1)

(2)

(3)

(4)

Fig. 9 : Human tenability diagrams

CONCLUSION

The procedure presented in this paper consists of a new integrated risk assessment method. Its specificity is based on the demonstration of interaction between smokes and human behaviour. This procedure is well suited for tunnel application thanks to the use of smoke dispersion models developed for this kind of application: NewVendis and FASIT.

The interaction between smoke dispersion models and the evacuation model is ensured by a simple exchange procedure of data. The use of evacuation model CRISP gives realistic results on users' situation during the evacuation. Indeed, in this model, people are assumed to adopt distinct behavioural roles, either naturally or due to training. Their behavior can be described in terms of actions, which may be abandoned, and substituted by new ones.

Tenability diagrams presented on the basic example have shown the benefit of this procedure. The results presented show clearly the interaction between smoke dispersion and subsequent human movements. Then, it becomes easier to understand the reason why people may die. This kind of approach gives considerable help to take efficient measures to improve the safety level of a tunnel.

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