HUMAN BEHAVIOUR IN ROAD TUNNEL SAFETY DESIGN: EVACUATION MODELLING VS ITALIAN RISK ANALYSIS METHOD (IRAM)

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ABSTRACT

Road tunnel fires are non-recurrent events which have led the researchers to investigate on the best risk analysis methodology. At the moment, the European Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European road network gives only general statements. Consequently, practitioners have often difficulties to define the best way to ensure the desired safety conditions inside tunnels. The Directive also gives the designer the possibility to use innovative safety methods and procedures which provide an equivalent or higher level of protection than current technologies. The study of the evacuation process requires the analysis of many factors and processes related to Human Behaviour, such as pre-movement times (e.g. reluctance to leave the vehicle), interactions between occupants, interactions between occupants and smoke, herding behaviours, way-finding, etc. IRAM - described in the Italian Guidelines for Road tunnel Safety design of 2009 - as well as a set of well known evacuation models has been analysed, taking into account the way the two methods represent the human behaviour-related factors. Conclusions on the use of the two methodologies are provided, focusing on their strength and weakness. Finally, possible developments and improvements in the two methods are given.

KEYWORDS

Road Tunnel Safety, Risk Analysis, IRAM, Evacuation Modelling, Human Behaviour in Fire

1. INTRODUCTION

The tragic events of the last twenty years have demonstrated that the impact of tunnel fires on the public opinion has been very strong [1]. In particular, the Italian situation is a very sensitive case because of the high number of road tunnels and the significant volume of traffic within them [2]. At the moment, the European Directive 2004/54/EC [3] establishes the requirement of a thorough and detailed risk analysis for the safety design of the tunnels in the trans-European network. Thus for achieving the appropriate safety levels and reducing the negative consequences of a hypothetical emergency scenario.

Nevertheless, the European Directive presents only general prescriptive standard requirements without providing a precise methodology for performing risk analyses. Consequently, the current state-of-the-art presents several methods in relationship to the national standards and/or guidelines of each country. The Art. 14 of the Directive provides derogation for innovative techniques in case they permit to obtain an equivalent or higher level of safety for the examined infrastructures. In this context, the use of a performance based design approach can be useful for evaluating the effectiveness of the different design solutions [4].

For this reason, there is a need to analyse the most common used methods in order to evaluate the possible differences in the safety design in relationship to the different approaches. A comparison between the most used method in Italy, the Italian Risk Analysis Method [5] and the application of Computational Modelling tools for evacuation simulations [6] is presented in this paper.

The two methods permit to perform the analysis of the evacuation processes by starting from the assumption that occupants leave their vehicles i.e. evacuations performed by driving vehicles are not taken into account. Consequently, the analysis of the evacuation process starts when there is a queue of stopped vehicles (e.g. driving behaviours during evacuations are not considered in this paper).

The first part of the paper describes the process of emergency evacuation. It is a very complex phenomenon that requires a holistic approach to the problem. The factors to be considered fall into two categories: physical characteristics and Human Behaviour-related processes. While the first type of factors is deterministic in nature and consequently easy to be considered, the variables related to Human Behaviour present difficulties in the phase of input definition due to their intrinsic randomness.

In this paper, the focus is on Human Behaviour because it plays a key role in the evacuation process [7,8] and the currently available tools may often show difficulties to reproduce the specific conditions that can happen in case of road tunnel evacuations. In addition, there is still a lack of data about the possible performances of humans in this kind of environments. This lack of information has to lead the safety designer to be very careful when performing a risk analysis (i.e. taking into account the uncertainty about human performances and processes).

Consequently, designers have to focus their attention on three different level of knowledge:

1) The aspects related to Human Behaviour in case of emergency scenarios in road tunnel fires;
2) The characteristics of the methodology they are using in order to perform the safety design (i.e. the risk analysis tools they are applying);
3) The limitations of the method in use to reproduce the aspects related to Human Behaviour.

An effective solution to the last point is to develop a comparative analysis between different methods in order to check the differences among them. The three above mentioned points are described in this paper for both the IRAM and the application of evacuation modelling tools. The way in which they take into account the Behaviour-related factors is analysed as well. Future developments and improvements within these two methodologies are also provided.

2. HUMAN BEHAVIOUR IN ROAD TUNNEL SAFETY

Road tunnels are unique environments with their own specific characteristics: underground spaces, unknown to users, no natural light, etc. which affect different aspects of Human Behaviour during emergency scenarios [7,8,9] such as pre-evacuation times (e.g. people may show vehicle attachment), occupant-occupant and occupant-fire interactions, herding behaviours, exit selection, etc. [10,11,12,13].

The events that are considered as critical for the specific case of road tunnels are fire, accidents with fire, dangerous material, flammable and toxic liquid spreading [5]. The most frequent behavioural responses to an emergency event could be categorized as evacuation, fighting or containing the fire and the notification of other individuals or the fire brigade [12].

The next part focuses the attention on the evacuation processes in case of fire and the occupant's behaviours playing a key role within them. The information about these behaviours can be obtained from data of actual accidents, experiments or drills. The most reliable studies are based on actual accidents, but these data are hard to collect due to the reluctance of the companies in charge of the tunnel management of sharing their databases due to privacy and safety issues. Furthermore, data from experiments and simulations can accuse lack of realism or be difficult to be extrapolated for other analyses. On the other hand, although the importance of collecting information from real tunnel fires is evident, experimental methods are required for the observations of human behaviour processes under different conditions [9]. By the way, there is not much experimental literature available. This work analyses firstly the current available literature in relationship to the different aspects of the human performances.

The influence that each variable may have on the evacuation process needs to be defined in order to provide an appropriate evaluation of the safety conditions in road tunnels. The literature presents studies on the impact of certain variables and processes. The most important variables related to Human Behaviour are pre-evacuation times, exit selection, social interactions and fire influence.

2.1. Pre-evacuation times

The pre-evacuation time is the time required for each occupant to understand what has happened (detection time) and the time spent to decide what to do (reaction time). This time is influenced by internal and external factors [10, 11]. The internal factors are related to the physical and socio-psychological characteristics of the occupants: their emotional states [7]; cultural background or training, past fire-related experience and knowledge of the environment and safety devices (i.e. the case of professional drivers [14]. External factors include social interactions. In fact, people are strongly influenced by the actions of others (i.e. to decide to get out of the vehicle or choose an exit). Other external factors include environmental conditions such as alarm systems, visibility conditions (e.g. emergency lighting system, exit visibility, smoke thickness, road signals, etc.). The perception of the danger of a selected group of occupants can also be influenced by their position with respect to the fire. In fact, occupants can have a direct perception of the danger, they can see only the smoke or the actions of the alerted people (or a combination of them) [15].

Several actions could be performed. Motorists may show vehicle property attachment and/or they can consider their cars as the safest place to be and, after shutting windows and ventilation, will remain seated in their cars [10]. In the experiments performed in the Benelux Tunnel, the results showed that users remain passive in the interior of their vehicles between 5 and 6 minutes [7]. Purser [13] analyzes the real case of the Mont-Blanc tunnel fire, estimating an average time of 30 s to leave the vehicles. In the experiments of Frantzich and Nilsson [9], participants open the door of the vehicle within 35 s.

2.2. Exit selection

This variable depends on the environmental conditions (distance, visibility, etc.), social interactions and the occupants’ knowledge of the geometry of the tunnel. In general, occupants can go towards the nearest exits, but in case of tunnel fire, emergency exits may similarly be even more deterring and unfamiliar than the tunnel itself [9]. Apart from the exit location, occupants also take into account the fire-related conditions, their familiarity with the exits and the exit visibility.

2.3. Social Interactions

The interactions between occupants are a crucial factor in modelling the evacuation process. Humans tend to be strongly influenced by the behaviour of others, regarding the decision to leave the vehicle as well as for the exit selection [9, 10]. There are two main types of interaction between the occupants during an emergency: "emerging groups" and "established groups” (i.e. family, friends, etc.). The emerging groups can arise and dissolve during the emergency. The natural behaviour of the established groups is to stay together and ensure that each member has been evacuated safely. In fact, their walking speed will correspond to the slowest user while response times and evacuation routes will be the same for the whole group.

2.4. Fire Influence

Fire can affect the occupant’s evacuation process. The smoke effects affect the walking speed and may cause the incapacitation of the occupants. These effects have been reported in the literature [13, 16, 17]. Unfortunately the scatter of the experimental results is wide and further investigation is still required on this topic. Radiation and temperature effects also affect the path of the agents.

3. THE ITALIAN RISK ANALYSIS METHOD (IRAM)

The Italian Risk Analysis Method [5, 18] is currently the most used method to perform risk analyses in the Italian tunnels. It is a combination of several methodologies put together in order to analyse the different variables affecting the safety of the tunnel. The methodologies that it takes into account can be resumed in these steps:

1. Probabilistic techniques able to identify and characterize the non-recurrent events affecting the system (functions of distribution and event trees);
2. Probabilistic techniques for the representation of the possible hazard scenarios (event trees);
3. Analytical and numerical techniques for modelling the development of the hazard conditions within the infrastructures (Computational Fluid Dynamics – CFD - models);
4. Stochastic techniques for the simulation of the evacuation process within the infrastructure (Monte Carlo Methods);
5. Graphical techniques for the representation of the risk related to the considered road tunnel (complementary cumulative curves);
6. Risk evaluation related to the risk acceptability theories.

3.1. Identification of the probability of the occurrence of non-recurrent events

The first step of the IRAM is the identification of the risk related to the possible occurrence of non-recurrent events. The starting point is the definition of the possible critical events related to the considered system. In a second stage the probability of the occurrence of these events is calculated. This estimation is performed using different approaches: 1) analysis of accident database (i.e. applying the Bayesian approach for the determination of the functions of distribution density of the non-recurrent event, 2) event tree techniques or 3) the evaluation of experts [5].

3.2. Representation of the possible hazard scenarios

The previous step has permitted the definition of the critical events affecting the safety conditions of the examined tunnel. The IRAM prescribes that critical events has to be defined following these rules:

1) The number of the considered critical events has to be reduced;
2) The selected events have to show an appropriate risk index in relationship to the type of the vehicles involved in the accident;
3) They have to be in line with the traffic circulation rules;
4) They have to include the geometrical and environmental characteristics of the infrastructure.

The above mentioned rules permit the definition of the event tree related to each specific infrastructure. The IRAM also prescribes standard event trees that can be used by the designer in relationship to a set of standard features of the road tunnels.

3.3. Hazard conditions modelling

This step involves the use of analytical and numerical techniques for the calculation of the development of the hazard related to the environmental conditions. Fire scenarios are the most critical for the safety of tunnel and the method prescribes the use of Computational Fluid Dynamics (CFD) methods for the representation of the fire evolution during the passage of time. These techniques have to be used to model the different scenarios defined in the event trees.

The IRAM suggests the values of the design fires to be considered. The interval of Heat Release Rate (HRR) Peak has to be between 15 and150 MW. The time to reach the Peak is prescribed in 13 min. The distribution to be considered is triangular or uniform.

3.4. Techniques for reproducing the evacuation process

During this stage the evacuation process is modelled taking into account the hazard conditions that have been calculated in the previous stage. The parameters affecting the process are categorized in 4 categories: Geometric, environmental, Demographic and Procedural.

The simulation of the egress scenarios needs a previous modelling of the vehicle queue within the tunnel. It is calculated taking as the fundamental parameter the distance between the vehicles.

The second phase is the simulation of the occupants' evacuation. The method uses a simplified technique that is based on the following variables:

1) Time needed by the occupants to leave the vehicle;

2) Walking speed of the occupants;
3) Walking path of the occupants;
4) Exit selection.

The simulation of the evacuation process is done by previously defined factors affecting the occupants' movement. Thus, the human flow is defined. Different conditions are also taken into account (i.e. ideal evacuation conditions, evacuation phases, and evacuation dynamics) and the basic information on the evacuation process are considered as well (e.g. occupant load, occupant positions, etc.).
The IRAM recommends the following average times to leave the vehicle (See Table 1). The walking speed of the occupants are also defined (See Table 2).

Table 1 - Time to leave the vehicles needed by different kind of occupants

Type of vehicle	Time to leave the vehicle (s)
Light Vehicle	300
Heavy Vehicle	90

Table 2 - Walking speed values under different visibility conditions

Visibility Conditions	Walking Speed (m/s)
Good	1
Low	0,5
Very Low	0,3

After defining the walking path of the occupants and the time needed to walk along that path, the Fractional Effective Dose (FED) is inserted in the calculation. Consequently, the Time available for the evacuation is compared with the hazard conditions of the environment along the path of the evacuation.

3.5. Graphical techniques for the representation of the risk

The risk is calculated as a social Risk [18] estimating the frequency of the critical event (F) in relationship to the associated number victims (N). The Social Risk related to a road tunnel is formulated as "*the risk of a non-recurrent event, for which the number of fatalities is equal or superior to 50 in a single event. It is not acceptable if the estimated frequency is higher than 1/500 per year (F=2*10-3 per year; N=50)*" [5]. The curve passing for this point with a gradient of -1, defines the threshold of tolerable Risk.

The IRAM prescribes the use of complementary cumulative curves in order to measure the number of fatalities for each critical event. It contains information on the frequency of the occurrence of a set of critical events and their possible consequences. The area under the curve defines the global risk indicator for determining the equivalent conditions among different design solutions.

3.6. Risk evaluation related to the risk acceptability theories

The ALARP (As Low as Reasonably Practicable) [5] principle is used to evaluate the acceptability of the risk conditions. In this way it can be also possible to define the effectiveness of necessary improvements in case the safety level is under the required level.

4. EVACUATION MODELLING FOR THE TUNNEL SAFETY DESIGN

The recent developments in Performance Based Design have lead to the development of a relevant number of computational tools for the safety designers. In this context, several evacuation models have been developed [6]. In fact, their application for different types of infrastructures is becoming common for the practitioners, including the road tunnel safety designers.

4.1. Classification of Evacuation models

Evacuation models can be categorized by the published description of their characteristics [6] or empirical tests of their claims [19]. Different modelling method (i.e. the sophistication that each model considers to calculate the evacuation times) can be defined. The three methods are Behavioural models, Movement models and Partial Behaviour models. Behavioural models incorporate occupants performing actions, decision-making processes and reactions due to the environmental conditions. Movement models move occupants from one point to another (generally a safe place). Partial Behaviour models primarily calculate occupant's movement, but implicitly reproduce the occupant's behaviour by pre-movement time distributions, overtaking behaviour, smoke influence, etc.

The deterministic or the stochastic approach can be used to insert the inputs inside the evacuation models [15]. The variability of the features of the agents - especially regarding the inputs related to Human Behaviour - could be better modelled through the use of distribution laws. The complexity of human features and actions during tunnel evacuations could be represented with difficulty using deterministic parameters (i.e. constant values for walking speed, delay times, etc.). The use of distribution laws gives the modeller the possibility to consider specific occupant features (in general or due to a particular condition), including them as a part of the distribution law.

In addition, the models permit to manually implement different groups, modelling a “social action” through assigning the same distribution laws to specific groups. Evacuation flows are reproduced in different ways. Occupants are usually assigned an unimpeded walking speed by the user and the simulation methods can be different, including:

1) Cellular Automata (CA): in which the agents move from a cell of a grid to another one.

2) Agent based modelling (ABD): agents are capable of interacting with the environments and/or other agents following a list of rules that guide their movement; therefore an agent is defined simply as “something that perceives and acts”.

3) Flow based modelling (FBM): occupant density is modelled as a continuous flow. A set of parameters permits to bypass social factors because the flow of the evacuation process can be estimated manipulating walking speed, physical constraints in walkways, density, and initial position of people,.

4.2. Evacuation modelling for studying tunnel evacuations

The analysis of the safety condition of a tunnel can be done by applying the evacuation modelling tools for the different scenarios of the critical event tree. The different types of evacuation modelling tools can present different degrees of sophistications and could present or not the possibility to simulate certain variables.

The authors have reviewed the published descriptions of four of the most used evacuation tools (FDS+Evac STEPS, Pathfinder and Simulex) in order to check their usability for road tunnel safety purposes. The software main features are resumed in the Table 3. This analysis is also based on previous studies of the authors in which the factors and processes related to Human Behaviour in road tunnel evacuations using different egress models have been tested [20].

Table 3. Main features of the considered evacuation models

Model	Pre-movement times	Exit selection	Herding Behaviour	Smoke Influence/ Incapacitation
FDS+Evac	Deterministic or Distribution laws	Exit selection Algorithm	No***	Yes/Yes
STEPS	Deterministic or Distribution laws	Exit selection Algorithm	No	Yes/No*
Pathfinder	Deterministic or Distribution laws	Deterministic or closest exit**	No	No/No
Simulex	Deterministic or Distribution laws	Closest exit	No	No/No***

*Currently under development
** An Exit Selection algorithm is currently under development
*** A research study has implemented this feature, but it is not available within the model

4.2.1. FDS+Evac

FDS+Evac [21] is a partial behaviour model that combines an agent-based model and a Computational Fluid Dynamics (CFD) model where the fire and the egress parts are interacting. FDS+Evac treats each occupant as a separate agent, using stochastic properties for assigning their characteristics. The model gives as results the position, the velocity, and the FED inside the computational domain at each discrete time step. FDS+Evac needs two different inputs for pre-movement times, the detection and the reaction time. It also permits us to use smoke density to trigger the evacuation process assigning a threshold value of it, but the smoke/heat detectors in FDS fire calculation cannot be used to trigger the movement of the agents. FDS+Evac uses game theoretic reaction functions and best response dynamics to model the exit route selection of evacuees. This method produces the directional field for egress towards the chosen exit door (the route is not the shortest one, but usually it is quite close to it). According to the fire influence on walking speed, door selection and incapacitation, the exits are divided into seven groups, so that each exit will belong to one group. The groups are given an order of preference. The user can also manually implement the exit familiarity by using the KNOWN_DOOR_PROBS command. In FDS+Evac the door selection can be manually influenced by radiation and temperature using the time-dependent parameters.

In FDS+Evac a sub-model for herding behaviour is proposed [22] but it is still in beta test. The first process is the gathering stage, in which people tend to walk towards each other. Then, people tend to walk together towards the selected egress path. Smoke density is used to influence the exit selection algorithm and walking speed in FDS+Evac. The modeller can manually modify the inputs about the unimpeded walking speed but the smoke influence on walking speed is fixed. FDS+Evac uses the results of the experiment by Frantzich and Nilsson [9]. The agents are not stopped due to thick smoke; they continue to move with a slower speed until they are incapacitated by the toxic effects of the fire. The incapacitation model is the FED concept introduced by Purser [16] In FDS+Evac the user can also choose the height in which the smoke is affecting humans.

4.2.2. STEPS

Simulation of Transient Evacuation and Pedestrian movementS (STEPS) 4.0 [23] is a movement/partial behaviour model. It is an agent-based model in which the path to the exit is calculated through a grid (CA). Uniform, standard normal and log-normal distributions can be inserted in STEPS. STEPS uses a unique parameter to input the pre-movement time, the *delay time* parameter. The two steps of the way-finding are the definition of the agent's target and the path to reach that target. Occupants score each possible target and choose the one with the lowest score. In addition, the insertion of blockage or exit events can be used to make some areas or exits unavailable past a certain time: this can affect people's evacuation route. The exit selection process is also defined using the “awareness” parameter when defining people targets. There are no herding behaviour sub-models, but it is possible to implement groups of people. Smoke-related factors currently do not affect the door selection (they affect occupant's walking speed using the results of the experiments by Jin and Yamada [16]. Surfaces of smoke concentration can be created in STEPS by importing FDS (this is the model used in this paper) or CFAST outputs [24, 25]. The implementation of the FED parameter is currently under development.

4.2.3. Pathfinder

Pathfinder 2010 [26] is a movement/partial behaviour model. It uses two ways to model the evacuation process. The first is a flow model, the SFPE method of Mowrer and Nelson [16], based on the calculation of the means of the capacity of the considered environment. The second methodology is an agent-based model (the Reynolds steering behaviour model redefined by Amor [26], in which congestion and queuing arise due to the model representation of human processes. Pathfinder calculates movement at discrete time steps. Step by step, it updates target points, calculates occupant's steering speed (in a different way depending on SFPE or Steering mode) and moves occupants. Pathfinder uses a unique parameter to input the pre-movement time, the *delay time* parameter through the use of uniform and standard normal distributions. Pathfinder permits us to assign a specific exit or the nearest one to every occupant. This means a deterministic approach to the problem. A more complex exit selection algorithm is currently under development. The absence of fire-related features does not permit us to directly evaluate the changing conditions of the environment (smoke density, door visibility, etc.). A contemporary use of a fire model is then necessary to evaluate the fire conditions.

4.2.4. Simulex

Simulex [27] is a partial behaviour model that relies on inter-person distances to specify walking speed of the occupants. The modeller has to select the occupant type from a set of possible options. Distance maps are used to direct occupants to the closest available exit. The user can create up to 10 different distance maps in the simulation. The pre-movement time parameter is the *Response time*. It can be assigned through random, triangular or normal distribution. Simulex also attempts to simulate overtaking, body rotation, side-stepping, and small degrees of back-stepping as it moves occupants throughout the building. No fire data can be directly implemented within the model. A recent study [28] has developed a Matlab algorithm to implement within the model the agents' incapacitation due to the smoke, but it is not available to the public.

5. COMPARISON BETWEEN THE METHODS

The evacuation modelling tools are useful to simulate the evacuation process within the risk analysis (corresponding to the point 4 of the IRAM). The differences between these tools and the IRAM can be studied taking into account the above mentioned behaviour-related factors (pre-movement times, exit selection, social interactions, and fire influence).

5.1. Pre-movement times

The definition of the average values of pre-movement times in tunnels is still controversial. The literature review in this paper shows that the scatter is still wide and there is still a need of further investigation. Current research studies like the METRO project [29] are investigating these values. The suggested value for applying the IRAM (See table 1) can be a useful starting point, but the designer needs always to make a case-by-case evaluation of the tunnel conditions (e.g. population characteristics, lighting conditions, safety equipments for increasing people awareness, etc.).

Evacuation modelling tools permit to perform sensitivity analyses of the key variables in order to check the impact it has on the final evacuation process [30]. They can permit a high level of accuracy because computational tools are very effective in performing this kind of studies due to the possibilities to include a wide range of values. The use of distribution laws is another way to take into account the possible variability in this parameter including random variables.

5.2. Exit selection

The IRAM suggests a designer evaluation of the factors affecting the occupant movement before the start of the egress calculation. It means that the possible evacuation flows are defined in advance by the user in accordance with the simulated infrastructure. Several conditions could be simulated and the designer has always to be very careful during the evaluation of the possible users' choices about exit selection.

Evacuation models can use different algorithm for the exit selection as we have reviewed in the Chapter 4. They can vary from a definition of the closest exits (Simulex, Pathfinder) or a deterministic choice (Pathfinder) until detailed algorithms that take into account different factors (STEPS, FDS+Evac). The advantage of using evacuation models derive from the fact that in the cases where the exit selection algorithm is detailed, the model will automatically select the routes of the agents helping this way the designer and leaving less room to his subjective evaluation of the evacuation routes. By the way, the application of egress models still need a detailed designer's evaluation of the possible singular features of the tunnel that can affect the users' exit choice.

5.3. Herding Behaviour

The variables and processes affecting herding behaviours are still under investigation and unfortunately there are not many available studies on the topic. The IRAM prescribes the designer to take into account this kind of variables. For this reason, the designer needs to be an expert of human behaviour processes in order to take into account the herding behaviour influence on the evacuation processes and provide reliable results.

The usability of many current evacuation models is yet questionable because some of them still do not consider the decision making process and the group behaviours of humans. The sub-model for herding behaviour in FDS+Evac can be a start for reaching a high-level degree of objectivity while simulating evacuation processes within the evacuation models. Unfortunately, the processes related to Human Behaviour still need further experimental validation in order to be reliable. Consequently, it is advisable that the safety designers perform sensitivity analyses or apply safety coefficients in order to take into account the uncertainty in the results.

5.4. Smoke Influence

The IRAM uses the FED to calculate if the simulated conditions are acceptable for the user during the evacuation processes in a set of selected path. The values provided by IRAM about the walking speed under smoke conditions (See table 2) are in line with the current available literature. At the moment, it is the most reliable way to consider the fire influence on the evacuation process, although the effects of smoke on people are based on old experiments [16].

Evacuation models vary substantially from this point of view. There are models in which the fire influence cannot be considered (Pathfinder) and there is a need of a contemporary use of a fire model to study the fire conditions within the tunnel. In this case it is not possible to directly implement this analysis within the evacuation process. There are models in which it is not possible to directly calculate the fire influence within the model, but a parallel use of fire models can be implemented to check the safety level of the infrastructure. FED (Simulex) or only smoke influence on walking speed (STEPS; but the FED implementation feature is under development in this model) can be implemented. They sometimes can also permit to perform a contemporary study about the fire evolution (corresponding to the point 3 of the IRAM) or import data from this kind of analysis (FDS+Evac). Consequently, the following points can describe the application of evacuation models:

1) No need to adjust the fire model output to perform the evacuation studies (e.g. FDS+Evac permits to simulate at the same time the fire and evacuation processes using FDS);
2) Direct comparison of the ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time) within the model;
3) Possibility of implementing several fire scenarios in a relatively short time.

6. CONCLUSIONS

Human Behaviour is a sensitive spot during the analysis of the tunnel safety conditions. This happens due to the fact that there is a lack of data about experimental literature and actual accidents. Underground accidents are not as frequent as accidents on open spaces and tunnel management organizations have shared their experiences in a limited and superficial way. This maybe happens to avoid questioning on their responsibility and useless alarmism on the users.

The IRAM and the use of Evacuation modelling tools represent at the moment two valid alternatives to perform risk analysis, although there is a need to go into more depth in the representation of human behaviour.

For this reason, designers have to take into account the lack of data about human behaviour and they have to use the results of them with appropriate safety coefficients when assessing the safety conditions of an underground infrastructure or perform sensitivity analysis of the factors that may cause uncertainty.

Future experimental works have to focus on the study of human behaviour-related processes in a way that the ideal future tools will leave less room to the designer subjective evaluation and provide a more objective analysis. In this context, a deep study of the human performances will permit to create reliable and validated ad hoc algorithms to simulate the different human behaviours (e.g. herding behaviour algorithms, smoke influence on walking speed, etc.) affecting the evacuation processes.

Another sensitive spot is the point 1 of the IRAM. In fact, the Identification of the probability of the occurrence of non-recurrent events needs an accurate analysis of the cause tree. Designers need to carefully analyse the influence of the different factors affecting the tunnel safety. In fact, cause tree analysis could sometimes lead to evaluate the existing tunnel conditions as not acceptable even before performing the analysis of the event tree of the different scenarios.

Finally, a systematic implementation of the best evacuation modelling tools within the IRAM could be an option to obtain more accurate results, taking into account the strength they have in modelling particular aspects of the evacuation processes. The recent developments of these models will permit in the future to have a reliable tool for assessing the study of the tunnel safety conditions. They will also enable to perform more accurate evaluations of the current risk conditions of the considered underground infrastructure.

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