Using 2D and 3D Modeling and Simulation for Emergency Situations Management

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Abstract- Safety in motorway tunnels has become a critical issue in the last years, especially after the accident happened in 1999 inside the Mont Blanc tunnel, causing 39 deaths and several dozens of intoxications and wounded people. After this tragic event, the European Union imposed stricter regulations and procedures for emergency situations inside road tunnels longer than 1000 m. According to this situation, the authors propose the use of M&S (Modeling and Simulation) in order to manage a tunnel evacuation after a fire exploding in consequence to an accident, taking into account a series of significant factors like the road signs position (new criteria have been introduced with new regulation), but also human factors which significantly affect the procedure outcome. First a 2-D simulation model has been developed using Java™ Software, in which the user can analyze the behavior of the people escaping and the dynamics of the fire exploded and, consequently, assess the effectiveness of all the emergency procedures and infrastructures. In particular, regarding the state variables related to the human behavior, the model takes into account the main aspects of PECS (Physical Emotional Cognitive Social) reference models, in which physical, emotional, cognitive and social factors have to be studied. The model presented in this work is in fact quite similar to the one described by (Schmidt, 2000), called “Adam’s World” [1] where Adam, a primitive man, lives in an environment having food sources where he can replenish his energy level, but also traps and danger points to be avoided in order not to consume his energy faster. The aim of the two models is the same: first of all preserve life and health, but the great difference between Schmidt’s model and the authors’ one is that in Adam’s World the social aspect is missing (Adam live alone in his world), while in the evacuation model social aspects can significantly affect the individual’s decisions. The evacuation model and its results are described and analyzed in the following sections and, in the final part of the paper, a description of a 3-D tunnel model devoted to study in particular smoke dynamics is provided.

Key-words: Emergency Procedures, Simulation, Human Behavior, PECS Models

1. Introduction

In the last decade safety in motorway tunnels, especially for those longer than 1000 m, has significantly increased its importance inside the European Union; this decision has been unfortunately driven by a tragic event like the Mont Blanc tunnel disaster of 24th March, 1999. The Alpine District countries (Italy, France, Switzerland, Austria, Germany…) have a very huge number of long tunnels, and so they take particular care in safety taking in the more restrictive criteria imposed by the Union (traffic lights, SOS columns, regular by-passes, etc…)

One of the most significant topics of this regulation is about road signs, which must be clearly visible even in smoke or fire conditions and, in some cases, providing an appropriate level of brightness by back illumination. For motorway concessionaires this represents a very significant managing cost.

For every two road tunnels in Europe, one is in Italy and, after a research led by German Automobile Club (ADAC) in cooperation with other 11 Automobile Clubs, including Italian ACI, the situation of Italian tunnels is not so good: in the years 2005-2008 22 Italian tunnels have been examined, 14 of them did not respect the minimum safety criteria with serious lacks (emergency exits missing, fire fighting system
inappropriate, etc.) and only 8 passed the exam with just the sufficiency [2].

Taking into account the current situation in Italy, the authors provided a research focused on the development of simulation models able to provide more effective measures for managing emergency situations. The case study is focused on a 4.5 km tunnel located in Northwestern Italy, considering important aspects of human behaviour like physical, emotional, cognitive and social factors, which can have a serious impact on the management of road signs positions and illumination.

The paper will be divided in different sections: section 2 will provide a brief description of PECS reference models is provided with a particular focus on Schmidt’s “Adam’s world”, while section 3 is focused on the evacuation model. Section 4 will provide a description of the 3-D model, developed for studying the smoke behaviour inside the tunnel, and section 5 describes the results obtained and presents some conclusions.

2. PECS Reference Models: Adam’s World

PECS is a multi-purpose reference model devoted to simulate human behavior embedded in a social environment [3]; according to this definition, human behavior presents a complex structure because considers four different classes of factors, or state variables: physical, emotional, cognitive and social. The human being is consequently - according to Schmidt - perceived as a psychosomatic unit with cognitive capacities embedded in a social environment (in fact PECS means Physical conditions, Emotional state, Cognitive capabilities and Social status).

PECS model is the natural evolution of the BDI (Belief Desire Intention) architecture [4], by now no more appropriated for modeling real social systems because too restrictive.

The four classes of factors of PECS reference models play a significant role in the behavior control: the model of the human behavior has to take into account the following state variables, in order to be comprehensible and predictable:

- Physical State Variables;
- Emotional State Variables;
- Cognitive State Variables;
- Social State Variables.

The modeling type of human behavior depends on the nature of the problem; it is not mandatory to model all the four classes of state variables and/or all the interactions among them; in fact, considering for instance Adam’s Model, the social aspect is missing, because Adam lives alone in his environment.

PECS model, however, allows modeling the greatest part of the complex systems considering the four main classes of human factors with their interactions.

The evacuation model presented in the next section considers all the four classes, adding the social aspect to Adam’s model; any case, the model presented is quite similar to the one developed by Schmidt: there are danger points to be avoided, lives and health to be preserved, the use of cognitive capacity in order to find the better solution in terms of signs interpreting and so on, but the main difference with Adam’s World consists in the presence of a strong social component, which was missing in Schmidt’s model. Other people could significantly affect the individual behavior, in terms of cognitive capacity and fear, in fact, without an appropriate cultural basis; the individual stretches to behave “as the others do”.

Adam lives in a world composed by a 12x12 cells grid; among them there are:

- neutral fields in which nothing happens;
- food sources where Adam can eat and replenish his energy level;
- high energy consuming danger points from which Adam needs to escape.

Figure 1 represents a possible configuration of Adam’s environment.

![Adam’s World](image)

**Fig. 1 – Adam’s World**

Schmidt’s Adam model considers different aspects:

- *Adam’s Environment*: Adam lives in a world that is dynamic and constantly changing. It contains food sources where he can replenish his health and danger points highly health-consuming. Adam has continually to deal with this environment.
- *PECS State Variables*: Adam’s physical state is represented by the energy level, while the emotional aspect is described by fear. Adam has also cognition of himself and his environment but lacks of social aspects because he lives alone in his world.
- *Changes of the internal variables*: The state variables are subjected to continuous changes during the simulation time. Changes occur in two ways:
autonomously and/or triggered by an input; for instance health or energy level is subjected to both changes, in fact it decreases slowly with time and, when Adam falls in a trap or in a danger points, the decrease is slighter. Vice versa, when Adam reaches a food source, his energy level increases, depending on the amount of food consumed, until it reaches a maximum value. Fear variable behaves in the same way: it decreases when Adam becomes more confident of himself and his world but slightly increases when Adam falls in trap.

- Deliberative and Reactive behavior: The first behavior type follows simple rules, driven for instance by leading motives like hunger drive or the need of thinking, while deliberative behavior needs a predetermined planning action to reach a determined goal.
- Internal and external actions: Adam’s actions repertoire contains external actions, which have impact on the surrounding environment like gathering a food source, but also internal ones, which only affect Adam himself, like the planning or the thinking action.
- Learning: Adam is characterized by cognition of himself and his world and, thanks to his experience, recognizes some processes of the world where he lives in, like the food regeneration process, knowing even better the time it takes for the food to grow again. However this cognitive process is not sudden, but it is a process in a continuous evolution, because Adam initially does not know the food growth speed, but he learns that gradually in order not to mistake.
- Forgetting: Adam is capable to learn but is also subjected to forgetfulness because he is human and his memory capacity is finite. For instance, when he visits a field after a long time of absence, he could not remember perfectly if this field is neutral or it contains a food source or a trap. In order to refresh his memory, Adam has to revisit that field.

The model described in the following section has several points in common with Adam’s model and PECS reference models, because, like Adam, the individual in the tunnel has to preserve his life avoiding danger points (fire, smoke), reaching the by passes (instead of the food sources) using the cognition to recognize the right road signs. In addition however he has to deal with other people that can affect his choices with their fear and their own behavior.

3. The evacuation model

The evacuation model presents two complementary and synergic modules with a graphic user interface (GUI):

- Data input and scenario creation module: it is implemented using bCAD software and it is capable to map the tunnel case study, to position the signs and the safety devices (fire fighting systems, SOS columns, etc…) along the carriageways, defining the brightness of the signs themselves with their height and other attributes. This module allows also to position the means (cars, trucks and buses) involved in the accident in order to create a simulation scenario.

- Evacuation detail module: This module is able to determine the flow conditions of the people at the by passes according to the input conditions predetermined.

The bCAD interface is similar to most of the commercial 2-D drawing tool like Autocad or similar, in fact the toolbar allows drawing different objects like lines, poly-lines etc… and, thanks to an “ad hoc” tool developed by the authors, it is possible to position objects inserting their coordinates in a database. Thanks to this application it is possible to dispose the cars involved in the accident, the signs, the safety systems and locate the fire starting point. The GUI allows also establishing the fire power.

The evacuation module allows the users to observe the fire evolution at different time steps. In particular it is traced:

- the evacuation paths of the users involved in the accident (yellow);
- the volume occupied by the smoke and the heat (red).

Figures from 2 to 5 represent some different screenshots of the model output.
The case study reproduces an accident in a 4.5 km long tunnel triggering a fire of 30 MW power starting from a truck, the accident involves several cars and also buses. The simulator outputs analyzed as KPIs (Key Performance Indicators) are:
- the number of people not escaped from the tunnel at the end of the simulation time;
- the number of people escaped after the simulation time;
- the number of people injured or intoxicated by carbon monoxide (CO) at the end of the simulation time;
- the minimum, maximum and average exiting time from the vehicles; it represents a sort of “reaction time” after the fire explosion;
- the minimum, maximum and average escaping time from the tunnel bypass, which is calculated starting from the fire exploding until the escaping from the bypass.

These outputs have been set as objective functions for a monovalent Analysis of Variance (ANOVA) devoted to evaluate the improvement provided by the new sign configuration respect to the original one. The results of the analysis on the main objective functions are shown in the tables from 1 to 3.

Table 1 – Monovalent ANOVA analysis (Involved people)

<table>
<thead>
<tr>
<th>Variation origin</th>
<th>$F_{\text{calc}}$</th>
<th>$F_{\text{tab}}$</th>
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<tbody>
<tr>
<td>Remained People</td>
<td>13.14</td>
<td>7.71</td>
</tr>
<tr>
<td>Safe Exit People</td>
<td>7.76</td>
<td>7.71</td>
</tr>
<tr>
<td>Injured People</td>
<td>2.18</td>
<td>7.71</td>
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Table 2 – Monovalent ANOVA analysis (Time of the people exit from the motor-vehicles)

<table>
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Table 3 – Monovalent ANOVA analysis (People exit time from the motor-vehicles)

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</table>

The results obtained clearly show how the new sign disposition significantly affects some objective functions like the maximum permanence time in the tunnel, but also the number of people remained in the tunnel after the simulation time and, even in a shorter measure, the number of the escaped people. On the contrary the alternative signs position does not affect the minimum and the average times and the number of the injured people.

In conclusion to this analysis, the alternative sign disposition improves significantly the intrinsic tunnel safety, increasing the number of the people reaching the safety.

4. The 3-D Tunnel Model

The authors also developed a 3-D model devoted to analyze the flows of the people escaping and, in particular, the smoke evolution dynamics inside the tunnel. The model is developed using specific 3-D modeling software: Blender™, by Blender Foundation. This software is open source and allows modeling non-linear systems and fluid dynamics. The 3-D reproduction of the tunnel is imported in another software, Wolverine Proof Animation 3-D™, that allows animated simulation. The aim of this 3-D model is to provide a feedback about the evolution of the smoke propagation that the evacuation model is not able to give, in fact smoke propagates mainly on the vertical axis, so a 3-D model is required to study the phenomenon; the choice to implement the tunnel model in Blender and then in Proof Animation is devoted to implement different scenarios with different conditions of sign positions and brightness, parameters highly affected by the smoke speed, as shown in the results in the following section.

Figure 6 represents a snapshot of the section of the 3-D model created.
This phase is under development and it will be completed in the following months.

5. Results and Conclusions
For the evacuation model other significant factors for improving safety have been identified:

- **Smoke speed**: expressed in meters per second, it is the smoke speed in the tunnel failing the forced draught;
- **Exit sign brightness intensity**: it is the brightness intensity of the exit signs by the By-pass;
- **Safe sign brightness intensity**: it is the brightness intensity of the other signs in the tunnel.

The objective functions assessed are the same discussed in the section 3 and, considering initially the first three (remained, escaped and injured people), the most significant impact is provided by the smoke speed: the faster is the smoke, the greater is the number of people remained in the tunnel, the Response Surface of Figure 7 shows these results:

![Fig. 7 – Output regressive analysis: Remained People](image)

Figure 7 demonstrates also that the sign brightness does not affect the number of people “trapped” after the simulation time, while the brightness of the exit signs has a significant impact on the second objective function: the number of the people safe at the end of the simulation time; in fact, respect to other signs which worsen the performance because “deviate” the people, bright exit signs guarantee an increasing of people who reach safety. The results of this analysis are shown in Figure 8.

![Fig. 8 – Output regressive analysis: Safe Exit People](image)

Even the number of injured and intoxicated people is affected strongly by the smoke speed, but in a less marked way respect to the number of people remained in the tunnel. RSM (Response Surface Methodology) results are shown in Figure 9.

![Fig. 9 – Output regressive analysis: Injured People](image)

Smoke speed affects also the average escaping time: the time decreases when the smoke is faster; because the people are afraid and so they abandon their cars faster.

Regarding the average permanence time in the tunnel, both the smoke speed and the exit sign brightness heavily affect this objective function: when smoke is faster people escape faster, but if the signs are brighter escaping time is longer, because they are visible for more time. The results of the analysis are shown in figure 10.

![Fig. 10 – Output regressive analysis: Average Permanence Time](image)

Concluding, this work proposed an innovative approach for managing a critical emergency situation such as a tunnel evacuation considering different sign positions and human behavior. For the evacuation the authors proposed a PECS model to study this phenomenon building a 2-D model. This model allowed “What if analysis” considering sign position and brightness in order to evaluate their impact on the model objective functions.

There is also a 3-D model under development that proposes to better study the dynamics of the smoke propagation inside the tunnel and the relationship with the crowd flow.

**Acknowledgements**

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References

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