Behaviour Models for the evacuation of a motorway tunnel

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Abstract – This work focuses on the human behaviour during an evacuation of a motorway tunnel. First of all all the type of signalization have been taken into account, according with the current legislation updated after the Mont Blanc Tunnel tragedy of March 1999. In order to study how people behaves in case of emergency an interesting methodology has been applied: Thomas Saaty's Analytic Hierarchic Process (AHP), based on matrix weight calculation.
This methodology has been implemented in a simulation model that considers different scenarios, based on the signs' position. All the scenarios then have been analysed and evaluated using well-known techniques such as Analysis of Variance (ANOVA) and Response Surface Methodology (RSM).

Key Words – Human Behaviour; Emergency Procedures; Simulation; Multicriteria Analysis

1. Introduction

The current legislation, updated following the serious accident occurred in the Mont Blanc Tunnel on March 24, 1999, imposes a series of road signs (back-illuminated and not) in the tunnel: indication of the stop areas, indication of the hydrants, two face signs noticing the nearer backward and downward by-pass, etc.. These installations represent a significant managing cost whose efficiency in case of accident should be totally demonstrated. The requirement to simulate the user behaviour during a tunnel fire arouse in order to detect the placing and illumination of the signs maximizing the structure safety. Methodologically it has been necessary at first to define which sides affect an individual choice in a potentially dangerous situation and then find an analytical solution to define both the behaviour choices (I remain in the car or run away, in which direction run away, etc) and the correct project ones (signs, illumination, air ventilation, fire extinguishing systems, etc).

The work has been carried out in cooperation with the A32 Turin - Bardonecchia motorway management (SITAF).

2. Behaviour model and simulation

The definition of which parameters affect an individual choice in a potentially dangerous situation like a tunnel evacuation can be re-conducted to a multi-criteria decisional problem, one of the most suitable methodologies is the AHP (Analitic Hierarchic Process) technique planned and implemented by the American mathematician Thomas L. Saaty

2.1 Analitic Hierarchic Process

The AHP provides for a distinction between the evaluation subject component and the objective datum. The decision maker detects a set of decisional alternative evaluation criteria and assigns to each criterion a percentage importance; then he assigns a score, which is the criterion impact on the decision. The score of each decisional alternative is the weighted average of each criterion scores on the decision multiplied by the weight assigned to each criterion. In the case concerned by the study it is necessary to evaluate the attractive character (weights) of some tunnel sign typologies, particularly:

The IsFireFight type: referring to the possibility to carry out active actions so as to limit the damage to the property and the life.

The IsExit type: pointing out the possibility to reach safety.

The IsPhone type: allowing to communicate with the road rescue service.

The IsSOS type: allowing to put in a state of alarm.

These signs will be more or less interesting as a function of the individual training and natural attitudes, particularly during the simulation three user typologies have been detected:

- **"Informed" User (or trained).** It is the user with the high culture in safety matter. This user will tend to choice the alternative able to save his life

- **"Uninformed" User (or not trained).** It is the user without specific technical knowledge. He will tend to preserve the property and life.
- **"Hero" User.** It is the user aiming to help and make himself useful for the others

For the above detailed user typologies, we have calculated, with the AHP method, the importance of the different signs. We explain as an example the detail of the procedure for the "informed" users. At first it is built up the behaviour local importance matrix (Table). The matrix building is made by asking ourselves the importance of the i_{th} line with respect to the j_{th}, column, for example for the line 1 (altruism) and the column 2 (property) it is necessary to make the following question for an "informed" individual which is the importance of the altruism with respect to the property? Seen that the behaviour importance displayed in the line (altruism), is grater than that in the column (property), we will make a number greater than 1 (on the contrary we would have put a number lower than 1). As it is pointed out in the hereunder table the life represents (for the informed individual) the most important behaviour/good.

Comportamenti	Altruismo	Proprietà	Vita	W	W Normalizzata
Altruismo	1	2	0,2	0,22	14,58%
Proprietà	0,5	1	0,2	0,21	13,80%
Vita	5	5	1	1,08	71,61%
				1,51	100,00%

Table 1 – *Behaviour matrix ("informed" individual)*

Then, we examine with the same logic, the daughter matrix, linking the present sign typologies with the detected behaviours.

Comportamenti	Altruismo	Proprietà	Vita	W	W Normalizzata
Altruismo	1	2	0,2	0,22	14,58%
Proprietà	0,5	1	0,2	0,21	13,80%
Vita	5	5	1	1,08	71,61%
				1,51	100,00%

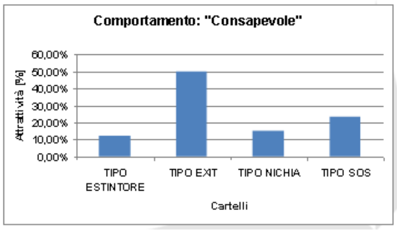
Altruismo	TIPO ESTINTORE	TIPO EXIT	TIPO NICHIA	TIPO SOS	W	W Normalizzata
TIPO ESTINTORE	1	0,33333333	0,5	0,33333333	0,35	10,61%
TIPO EXIT	3	1	2	0,5	0,81	24,38%
TIPO NICHIA	2	0,5	1	1	0,86	25,70%
TIPO SOS	3	2	1	1	1,31	39,30%
					3,33	100,00%

Proprietà	TIPO ESTINTORE	TIPO EXIT	TIPO NICHIA	TIPO SOS	W	W Normalizzata
TIPO ESTINTORE	1	0,2	0,5	0,5	0,48	16,65%
TIPO EXIT	5	1	0,333333333	0,5	0,52	17,88%
TIPO NICHIA	2	3	1	0,33333333	0,58	19,85%
TIPO SOS	2	2	3	1	1,33	45,62%
					2,91	100,00%

Vita	TIPO ESTINTORE	TIPO EXIT	TIPO NICHIA	TIPO SOS	W	W Normalizzata
TIPO ESTINTORE	1	0,2	0,5	0,33333333	0,20	11,74%
TIPO EXIT	5	1	5	4	1,05	60,95%
TIPO NICHIA	2	0,2	1	0,5	0,21	11,95%
TIPO SOS	3	0,25	2	1	0,27	15,36%
					1,73	100,00%

Table 2 – *Matrix of the road sign importance as a function of the behaviours ("informed" individual)*

By finally multiplying the local matrix importance (normalized W) we obtain the global importance or sign attractive character. The Fig. 1 shows as the Exit panel, is the most attractive for the "informed" user (complying with that said before).



Tipologe Cartelli	Attrazione
TIPO ESTINTORE	12,25%
TIPO EXIT	49,68%
TIPO NICHIA	15,05%
TIPO SOS	23,03%

Fig. 1 *Global importance of the signs for the "informed" individual*

Analogously to what illustrated for the "informed" user we calculate the tunnel sign attractive character for the other individual typologies. By stopping our attention on the "uninformed" user, representing in some way the common car driver, it emerges as it does not exist a sign more attractive than others (on the contrary this happens for the informed individual). The greater is the number of visible signs in the tunnel and the lower will be the probability that the Exit sign attracts the user.

Tipologe Cartelli	Attrazione
TIPO ESTINTORE	14,64%
TIPO EXIT	22,74%
TIPO NICHIA	23,01%
TIPO SOS	39,61%

Tipologe Cartelli	Attrazione
TIPO ESTINTORE	50,19%
TIPO EXIT	8,58%
TIPO NICHIA	15,62%
TIPO SOS	25,62%

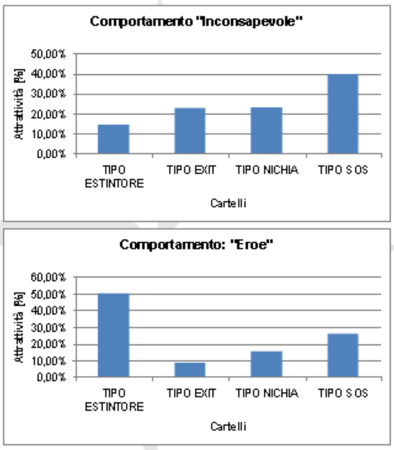


Fig. 2 – *Sign global important for the "uninformed" and "hero" users*

2.2 Behaviour model logic scheme

In the previous chapters we have seen as it is possible to objectify the tunnel sign attractive character for each individual concerned by the accident, now it is necessary to analyse how this behaviour acts in the time during the simulation. Schematically:

- The individual is "activated" (simulation beginning) in the post-event condition with a "normal" respiratory frequency and intoxication level and a particular behaviour attitude (informed, uninformed and hero).
- The individual takes some time to be aware of the situations in which find himself (he is still inside the car).
- Subsequently, he exits from the car (the exit from the car is modelled as a queue,

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not all the people inside the car shall exit simultaneously but one after the other).

- Once exited from the car, the individual is in front of a series of behaviour choices, which determinate the path and then the safety:
- First Step. The individual perceives according to the physical conditions of the place where find himself (ex. heat, smoke) a sign and possible target subset; he elaborates an eventual path towards the chosen target by excluding from the alternative those that cannot be followed or dangerous. The choice is rational and depending on the instinct and the meaning that the individual gives to that around him (importance assessment according to the AHP multi-criteria analysis).
- Second Step. The individual, after having done his rational choice, evaluates the distance to cover and, if the physical and environmental conditions make it possible, begins to run towards his target. Along the way he tries to evaluate, among the possible alternatives, the shortest path among the practicable ones (obstacles, heat). When he is near his target, he slows his run and begins to walk.
- Third Step. It can occurs in two different moments, depending on the fact that the individual would have attained or not his final target. In the first case, we suppose that the met sub target (sign/panel) can condition him to pursue towards a following target. In the second case the individual can re-evaluate his first choice and change his destination.
- With the time passing the individual breathes the smoke and the carbon monoxide eventually in the tunnel and intoxicates. Also the heat produces a damage (hyperthermia and burns).

Iteration of the last two points until the safety attainment or the death.

In this way we have a behaviour model which is affected in an autonomous way by the individual instinct when the same is left "without guide" while it is leaded by the signs if suitably placed and illuminated. It should be still observed finally that the individuals have also "complicated" behaviours since there is also the latent instinct to come back to their cars (as widely shown by the existing films). This behaviour is residual with respect to the supplied indications and "erodes" the rational capacity; the time passing inside the tunnel (may be doing the ping-pong between the car and the first visible panel) can cause anxiety and panic states. The panic inhibits the rational choices in the alternatives.

3 The simulator graphic interface

The simulator graphic interface (GUI) substantially consists of 2 complementary and synergic modules:

1. ***Data input and scenario creation module.*** It is built on bCAD and allows to map the tunnel concerned by the study, place the signs along the carriageways, define the sign attributes (luminosity, height, etc..) place the systems and create the accident reference scenario (car and truck disposition).
2. ***Evacuation detail module.*** It determinates the efflux conditions at the safety exits according to the organised operating conditions.

The bCAD environment is quite similar to any sold 2D drawing tool (like autocad). In the toolbar and through the menu we can draw lines, poly-lines insert objects, etc.. The DIPTEM application allows, moreover, to supply references through a database to the sign position (x, y, z coordinates), the location of the vehicles involved in the accident and their characteristics, the fire starting point and its power.

The tunnel evacuation module allows to observe by different temporal instants the fire development. Particularly it traces:

1. The evacuation paths of the users involved in the accident (yellow).
2. The volume occupied by the smoke and the heat (red)

The Figs. 3 – 6 show an example of model output:

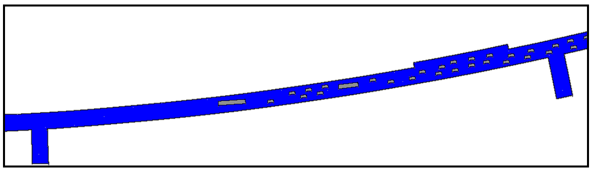


Fig. 3 – *Tunnel at the simulation beginning (t=0)*

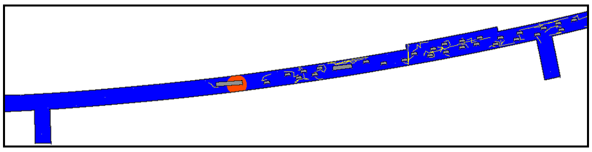


Fig. 4 – *Tunnel after 30 seconds from the fire beginning*

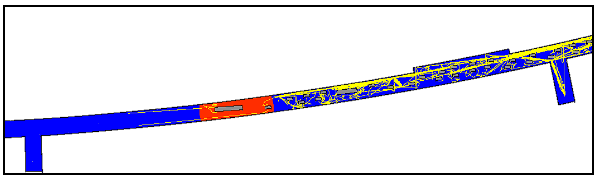


Fig. 5 – *Tunnel after 60 seconds from the fire beginning*

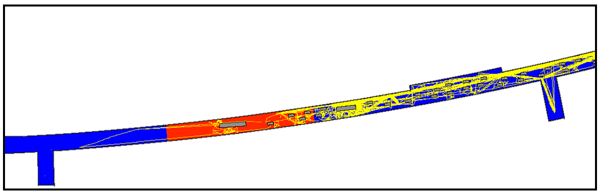


Fig. 6 – *Tunnel after 120 seconds from the fire beginning*

4 Alternative and current arrangement of the tunnel signs

As we referred at the paper beginning, the enforced standards concerning the motorway safety provides the installation in the tunnel of a high number of panels. We can think that it exists a panel over dimensioning at the disadvantage of the important sign selectivity (typically the exit by the by-pass). This conviction is congruent with the AHP analysis tables displayed in the Fig. 2. For the "uninformed" or not trained user (representing the type user), the higher is the visible sign number and the lower will be the probability to follow the exit one. In this sense we have elaborated an alternative sign disposition configuration in cooperation with the SITAF personnel. To evaluate the eventual performance differences between the current tunnel layout and the elaborated alternative disposition, the simulator outs have been the subject of ANOVA analysis (ANalisys Of VAriance). Particularly the observed answers as performance indicators have been:

1. Number of people remained in the tunnel (not exited) at the end of the simulation launch (7 minutes).
2. Number of people exited after the 7 minutes of simulation.
3. Number of "injured" people (CO intoxication, damage by presence of heat) at the end of the simulation launch
4. Maximum, average and minimum time of the people exit from the motor-vehicles. It represents the time between the fire beginning to the people exit from the motor-vehicles.
5. Maximum, average and minimum time of permanence in the tunnel. It represents the time between the fire beginning to the people exit from the tunnel through the By-Pass.

In the light of the ANOVA test results (Fig.s 7-9) we can conclude that:

For the two configurations, there are significant differences on the studied performances.

- The greatly sensible out-put at the panel configuration varying is the maximal time of the user evacuation from the tunnel, followed by the number of people remaining "trapped" inside the tunnel after 7 minutes from the accident (with the tunnel already full of smoke).
- The time of staying in the car before to decide to run away does not result (as predictable) affected by the different panel arrangement.

According to what has been examined, it results evident that <u>with an alternative luminous panel arrangement it is possible to increase the tunnel intrinsic safety (in terms of people managing to reach safety).</u>

	$F_{calculate}$	$F_{riferiment}$
Remained People	13,14	7,71
Error		
Total		
Safe Exit People	7,76	7,71
Error		
Total		
Injured People	2,18	7,71
Error		
Total		

Fig. 7 – *Monovalent ANOVA analysis (Involved people)*

	$F_{calculate}$	$F_{riferiment}$
Min Excape Time	3,52	7,71
Error		
Total		
Max Excape Time	0,10	7,71
Error		
Total		
Averange Excape Time	0,05	7,71
Error		
Total		

Fig. 8 – *Monovalent ANOVA analysis (Time of the people exit from the motor-vehicles)*

	$F_{calculate}$	$F_{riferiment}$
Min Permanence Time	2,43	7,71
Error		
Totale		
Max Permanence Time	13,52	7,71
Error		
Total		
Averange Permanence Time	0,12	7,71
Error		
Total		

Fig. 9 – *Monovalent ANOVA analysis (People exit time from the motor-vehicles)*

5 Results and significant character of the concerned factors

After having shown the configuration superiority without any sign typology, we stop our attention on which other factors affect the tunnel safety. On the SITAF suggestion, we have considered 3 elements:

- **Smoke speed**. It is the speed expressed in meters per second, with which the smoke advances in the tunnel failing the forced draught.
- **Exit sign luminous intensity**. It represent the luminous intensity of the exit signs by the By-pass.
- **Safe sign luminous intensity**. It represents the luminous intensity of the other signs in the tunnel.

The experimental campaign result is displayed in the Fig. 10

Exp #	SmokeSpeed [m/sec]	ExitPanelsEmission [lux]	SafePanesEmission [lux]	RemainedPeople	SafeExitedPeople	InjuredPeople	MinExcapeTime [sec]	MaxExapeTime [sec]	AverageExapeTime [sec]	MinPermanenceTime [sec]	MaxPermanenceTime [sec]	AveragePermanenceTime [sec]
1	0,5	450	450	25	189	1	9,22	127,65	43,54	24,06	408,81	142,92
2	0,80	100	100	41	172	2	9,13	125,13	38,83	21,22	389,69	128,75
3	0,20	800	100	2	212	1	9,02	126,26	44,76	20,86	412,36	154
4	0,50	450	450	19	195	1	9,02	127,23	44,94	21,95	401,39	136,76
5	0,20	100	800	10	204	1	9,01	125,23	44,5	18,3	403,92	150,79
6	0,20	100	100	5	208	2	9,15	126,12	44,46	24,02	414,78	147,5
7	0,20	800	800	9	205	1	9,05	125,47	44,32	25,64	404,12	152,3
8	0,50	450	450	22	192	1	9,02	125,61	42	25,43	402,08	146,73
9	0,80	100	800	34	179	2	9,07	125,07	38,23	19,82	400,76	133,46
10	0,80	800	100	38	176	1	9,01	125,19	38,58	26,55	404,77	138,13
11	0,80	800	800	34	179	2	9,14	125,38	39,3	21,08	394,35	137,47

Fig. 10 – *Experimental campaign at the considered factor changing*

<u>Remained People & SafeExitPeople & Injured People</u>

The number of people remaining trapped in the tunnel at the end of the simulation is affected both by the smoke spreading speed and the sign luminous intensity. Particularly the smoke spreading speed is greatly the most significant factor. The greater is the speed and the higher is the number of people who don't manage to reach the safety.

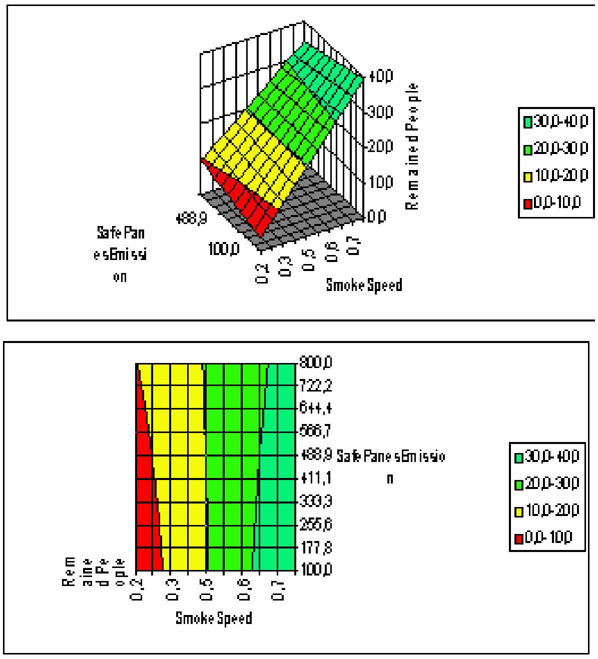
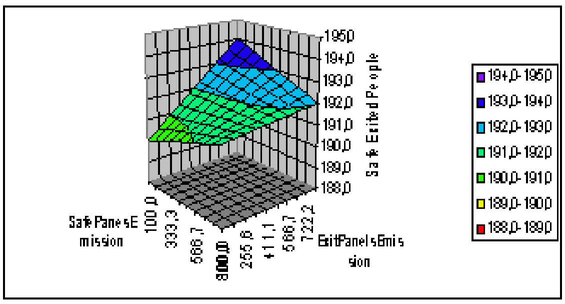


Fig. 11 – *Output regressive analysis: Remained People*

The Fig. 11 points out as at the smoke spreading speed increasing, the sign luminous intensity becomes irrelevant (the same behaviour with 100 cd/m^2 or with 800 cd/m^2), on the contrary in case of low smoke spreading speeds, at the sign luminosity increasing it follows an increase of the people who reach the safety. In other words, once the smoke invades the tunnel it does not exist a luminous intensity value, among those allowed by the enforced standards able to orient the people towards the exit way. The regressive model points out, moreover, as the Exit signal must prevail with respect to the other signs (Fig. 12). The Safe signs create indeed a background "noise" worsening the tunnel safety (in terms of users managing to reach the exit). It is a phenomenon which increases at the sign luminous intensity increasing.



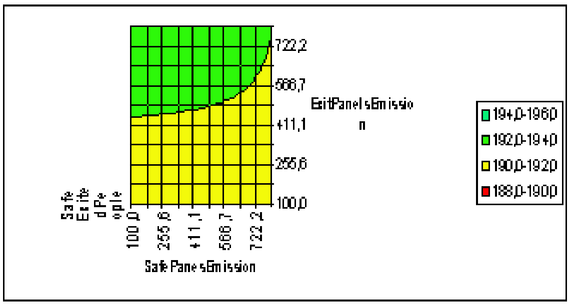


Fig. 12 – *Output regressive analysis: Safe Exit People 1*

Finally, for as concern the people exiting injured/intoxicated from the tunnel, also this parameter is affected by the smoke spreading speed but in a less marked way (Fig. 13).

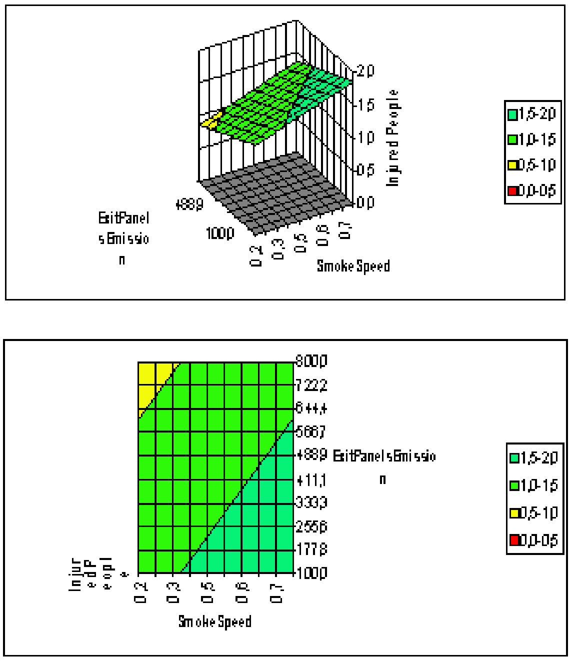


Fig. 13 – *Output regressive analysis: Injured People*

Min, Max and Average Escape Time

The waiting time inside the motor-vehicles, before to decide to run away is barely affected by the at stake factors. It exists only a slight dependence from the smoke speed on the waiting average time. The more rapidly the users see to arrive towards them the smoke and the more quickly they will decide to abandon the motor-vehicle and run away.

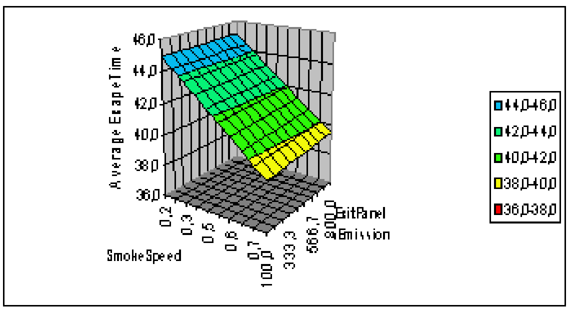


Fig. 14 – *Output regressive analysis: Average Escape Time*

Min, Max and Average Permanence Time

As for the waiting time in the car it does not exist significant variations about the maximum and minimum time spent to reach the safety. On the contrary the average time spent in the tunnel to reach a safety exit is affected both by the smoke speed and the sign luminous intensity. Particularly with the smoke speed increasing, the average stay time in the tunnel of the people who did not managed to reach the safety decreases. In other words, or they reach safety immediately by making the right choices or at the smoke arrival time is too late. In this sense the sign luminosity increases the permanence time in the tunnel by mitigating the smoke presence effect.

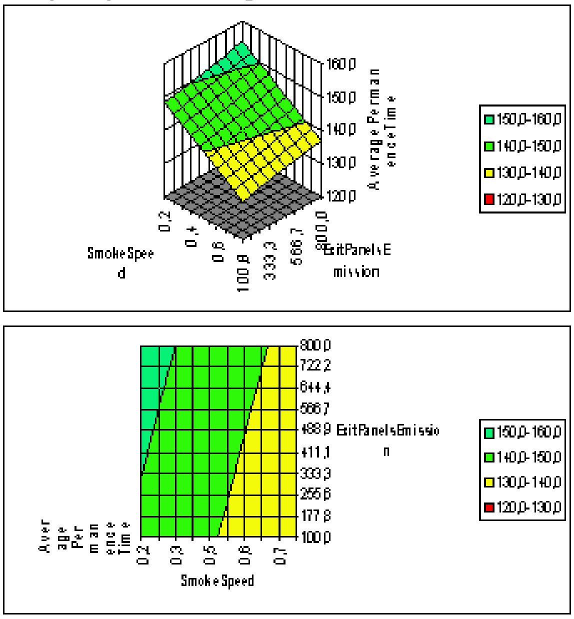


Fig. 15 – *Output regressive analysis: Average Permanence Time*

6 Conclusions

The regressive analysis on the system variables pointed out some elements, which significantly affect a tunnel safety. Particularly the smoke speed represents the most important factor. It is necessary to avoid their propagation towards the area occupied by the users exploiting forced draught systems (ventilation) and in any case by avoiding any manoeuvre aiming to stimulate the smoke movement towards this area.

For as concern on the contrary the panel arrangement and their luminous intensity, the analysis pointed out as it is not many efficacious the sign redundancy. Failing a base training (culture) about the safety, any panel has a similar attractive capacity. In order to increase the sign prevalence bringing to a right behaviour, or we act on the absolute number of panels in the tunnel, by keeping away the "not useful" ones or you act on their luminosity. In this sense the scenario elaborated by SITAF involves both sides. On one

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hand it reduces the sign absolute number by eliminating the double side ones and reducing the carriageway signs, on the other hand it rules the green exit sign by the by-pass at a higher luminous intensity than the others.

The DIPTEM working team believes moreover that it is possible to develop a simulation model carried out by implementing the following points:

WP1:Development of a approximated model of smoke dispersion in the tunnel and user behaviour simulation face to the smoke front intended as signal.

WP2: Development of an interaction model among the individuals involved in the accident in order to introduce the social behaviour (ex. Gregarious behaviour, etc.).

WP3: Development of an intervention model and interaction with the help command and control chain able to analyse the times and the modes of activation of the emergency teams.

WP4: Interaction development (Approximated model) between the ventilation regime organised in the tunnel and the smoke and carbon monoxide spreading (CO).

WP5: Development of a further simulation scenario set according to the carried out practice as well as the information received in the Project development.

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