RAIL TUNNELS RISK ANALYSIS: THE EFFECTS OF INFRASTRUCTURE AND FIRE CHARACTERISTICS

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ABSTRACT

The Italian standard on "Rail tunnel safety" have identified the minimum safety requirements for each type of rail tunnel. This standard also introduces two types of Risk Analysis (Base and Extended) to be performed in order to verify the fullfilment of all safety requirements and to compare the tunnel risk level with fixed acceptability thresholds.

In this study a methodology to conduct an Extended Risk Analysis was applied in order to allow to evaluate the heat and toxic gasses concentrations inside the tunnel due a fire on a train coach and to calculate their diffusion and their effects on passengers in function of infrastructure, train and fire characteristics. The used procedure allows to account for tunnel geometric characteristics (section and sidewalks number and width), vehicle characteristics (type of train and number of passengers) and fire event conditions (Heat Release Rate, Heat Release development time, toxic gasses type and concentration). The application of this methodology allows to estimate the saving people likelihood and the number of expected deaths as a function of the distances covered by each passenger depending on different accident scenarios and on evacuation procedures and tunnel characteristics.

A sensitivity analysis has been conducted in order to identify the influence of all parameters on passengers evacuation capacity, highlighting the effects of different parameters such as air speed and temperature inside the tunnel.

An analysis on different tunnel sections has been conducted in order to identify infrastructure effects on saving people likelihood.

This methodology could also be useful as a design tool in order to identify the best design, construction and management options to increase safety levels. It could also be used to define the most effective evacuation procedures for each emergency scenario. In this study the effects of the central footpath in double track sections have been investigated.

Keywords: risk analysis, rail tunnel safety, fire safety

1. INTRODUCTION

Italy is highly involved in road and rail tunnel safety due to the characteristics of its territory which often require long tunnels to cross mountain area. Actually in Italy there are 16'000 km of railways with 2'000 tunnels for a total of 1'400 kilometres, other 24 tunnels longer than 1 km are under construction and 23 in project, this means other 375 km of railway tunnels [CASALE, 2006]. Figure 1 shows the amount of tunnels longer than 1 km characterizing European countries, thus clearly shows that Italy is the country with the main tunnel network in Europe. Considering the percentage of tunnels in respect of the entire network Italy has the second higher value preceded only by Switzerland (Switzerland 9.4%, Italy 6.5%, Norway 3.2%) [LOFFREDO, 2006].

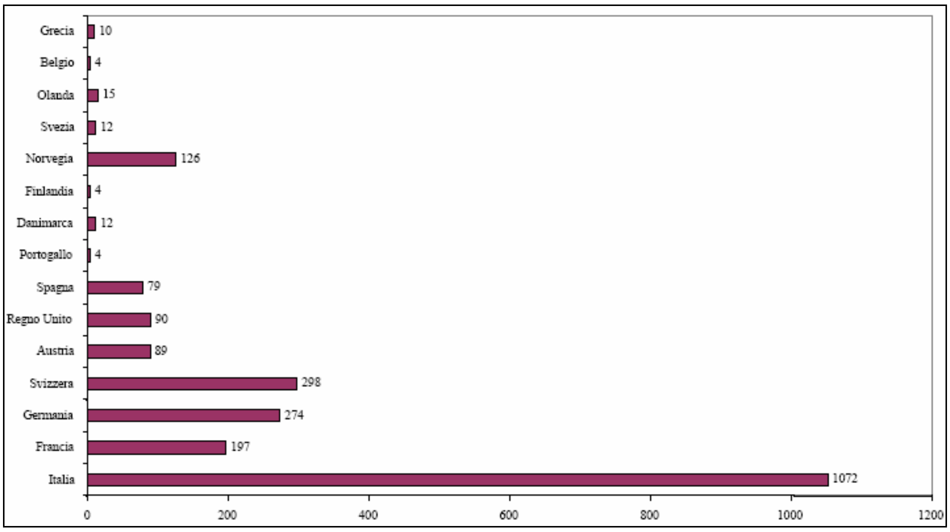

Figure 1: Tunnels longer than 1000 m development in Europe [LOFFREDO, 2006]

A preliminary evaluation of tunnel accident probability could be done considering the index referred to the entire Italian network. A comparison between Italian data (performed by Trenitalia S.p.A.) and those belongings to Germany and France is contained in Figure 2.

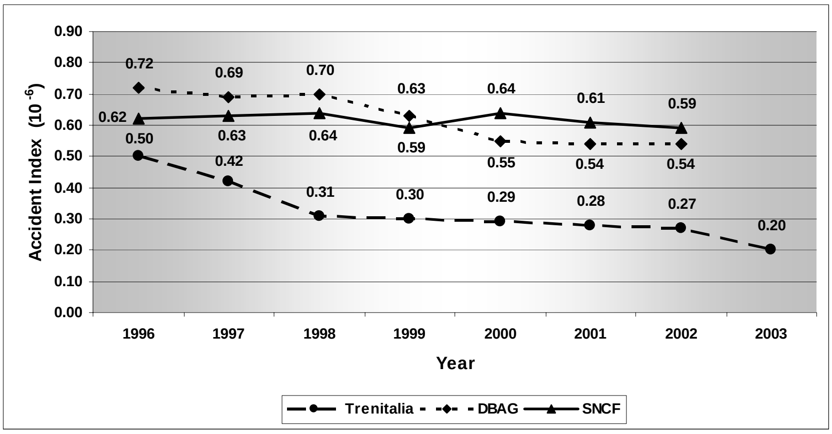

Figure 2: Accident Index comparison between Italian, French and German railway networks

To fix an accident index related to tunnel environment the category "Accident – Anomaly situations during circulation" have been considered. Under this denomination all the events happened in motion such as: train collision, locomotive or carriages derailment, locomotive or carriages fire, obstacles in clearance gauge can be considered. For this events category a percentage of 38.7% has been evaluated in respect to the total accident amount that are mainly "Manoeuvres accident" [1]; the proposed percentage includes both U.I.C. (Union Internationale des Chemins de Fer) accidents [2] and light accidents.

Assuming, for the Italian railway network, an average accident index of $i_i = 0.3 \cdot 10^{-6}\ accidents/train \cdot km$, the risk exposition of a railway tunnel can be characterized by an accident index equal to about $p_i = 0.12 \cdot 10^{-6}\ accidents/train \cdot km$. In only a limited portion of these events the train, after the accident, will not be able to be conducted outside the tunnel, as the standard procedure requires, and will stop inside the tunnel. The risk analysis takes into account only of these scenarios.

2. EXTENDED RISK ANALYSIS METHODOLOGY

Italian standard on railway tunnel safety [D.M. 28/10/2005] introduces the extended risk analysis as an instrument to fix and analyze safety conditions in tunnel longer than 9 kilometers or longer than 2 kilometers and characterized by high traffic or inversion slope altimetry.

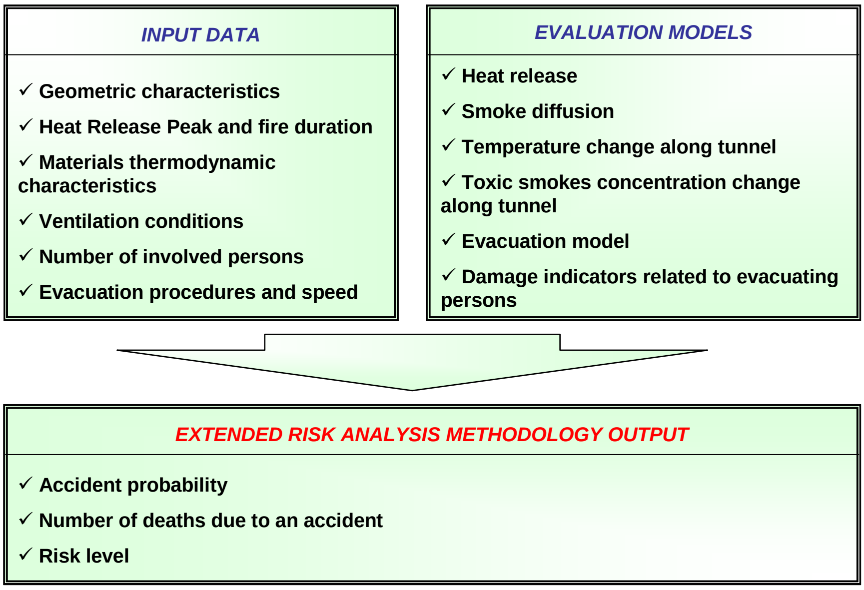

Figure 3: Extended risk analysis input-output data

A procedure to perform an extended risk analysis with reference to accident scenarios involving fires events on train stopped inside tunnels has been proposed by Pezzati et alii [PEZZATI, DOMENICHNI, MARTINELLI, CARA 2007]. It is based on a series of simulation models allowing to evaluate the accident probability, the number of fatalities and the tunnel risk level as function of the input variables specified in Figure 3. The considered models are:

- ✓ Heat release: heat release is assumed to be a quadratic time function since it reach the peak, as proposed by Mattias Person [PERSSON, 2002];
- ✓ Smoke diffusion: the applied hypothesis is to have natural ventilation with a 1 m/s speed, smokes mould an homogeneous mix with the air contained in the tunnel and leave free of smoke the windward tunnel portion [PERSSON, 2002; CASSINI, HALL, PONS, 2003], critical ventilation velocity and backlayering phenomenon have been considered too [HWANG, EDWARDS 2005; HESELDEN 1976];
- ✓ Temperature change along tunnel: heat flow irradiated by the fire has been estimated applying the relation proposed by Engelhard [ENGELHARD, 1997]. Fire smokes temperature has been valued considering the Society of Fire Protection Engineers indications [SFPE, 2002]
- ✓ Toxic smokes concentration distribution along tunnel: to fix toxic smokes concentration in each tunnel section in any moment a Swedish model has been considered [BERGQVIST, FRANTZICH, HASSELROT, INGASON, 2001]
- ✓ Evacuation model: consciousness, reaction, evacuation and movement time have been evaluated. Consciousness time depends on fire development speed

and detecting sensors, it has been fixed equal to 8 minutes [CARA, S.; MARTINELLI, F.; DOMENICHINI, L. (2007)]. Reaction time is a function of passengers behavior, alarm announcements, number of multiple choice possibilities; it has been considered part of the consciousness time. A first passenger evacuation time equal to 30 seconds has been used. Movement time is the one used by passengers to reach the nearest exit or refuge, in this study the covered distance has been evaluated considering a walking speed of 0.6 m/s as proposed by the Italian Standard. [D.M. 28/10/2005; PERSSON, 2002]

✓ Damages indicator: Fractional Incapacitating Dose (FID) indicators have been considered as proposed by ISO/DTS 13571 standard [ISO/DTS 13571, 2001].

3. EFFECTS OF INFRASTRUCTURE AND FIRE CHARACTERISTICS

3.1 Reference scenario

A sensitivity analysis of the developed risk analysis procedure has been performed in order to identify the main parameters influencing the passengers covered distances. A base condition, in accordance with the Italian standard, has been identified and the model has been applied to a reference scenario.

The reference scenario is defined by the parameters showed in Table 1; the ten parameters in bold type are those investigated in the sensitivity analysis.

Table 1: Reference Scenario Model Parameters

	Symbol	Description	Unit	Value
Fire Design Parameters	**Q**	**Heat Release Rate**	**MW**	**10**
	t_1	**Release time**	**min**	**10**
	Δt	**Fire duration**	**min**	**30**
Environment Characteristics	α_c	Heat convection transfer percentage		70 %
	T_0	**Air temperature**	**°C**	**20**
	A_T	**Tunnel section area**	**mq**	**74**
	P_T	Perimeter	m	33
	u	**Air speed**	**m/s**	**1.0**
	ρ_0	Air density inside tunnel	Kg/mc	1.201
	c_p	Air specific heat	KJ/Kg°C	1.007
Toxic Smoke Emissions	D_h	Tunnel hydraulic diameter	m	8.97
	Y_{CO}	**Fraction CO per gram burnt fuel**	**g/g**	**0.040**
	Y_{HCN}	**Fraction HCN per gram burnt fuel**	**g/g**	**0.009**
	ΔH	**Effective heat released for each fuel kilogram**	**MJ/Kg**	**45**

	r_0	**Stochiometric heat coefficient**		**4**
	X_∞	Oxygen sea level concentration		20.70 %

The reference scenario, whose characteristics are summarized in Table 2, is characterized by a nine coaches train with 80 seats each and a filling coefficient of 90% for a total of 648 passengers plus four people of technical staff.

Table 2: Reference Scenario characteristics

Description	Unit	Value
Train involved	N°	1
Coaches	N°	9
Seats per coach	N°	80
Filling coefficient		90 %
Technical staff components	N°	4
Fire position	Coach n°	1
People followed by smokes	N°	616
Door opening criteria		Simultaneously
Footpath	N°	1
Analysis duration	min	120

The worst condition have been analyzed, referred to a fire occurred in the first coach, an air direction equal to the evacuation one, that means all coaches reached by smokes, a tunnel with only one lateral footpath and a simultaneously door opening procedure.

Figure 4 shows the base case evacuation scenario, considering 652 people on the train, 36 exiting from the first door, so evacuating against wind direction, there are 616 passengers that must leave the accident site followed by smokes.

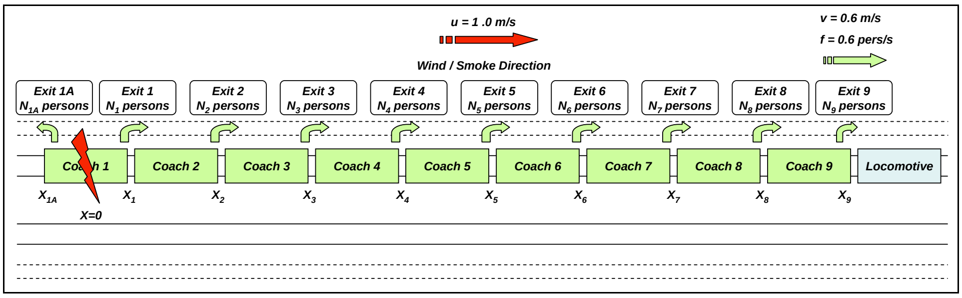

Figure 4: Reference evacuation scenario

In order to best explain the model sensitivity the influence of ten parameters on passengers covered distance has been studied. As performance indicators the 85th and 50th percentile of passenger covered distance have been considered, this means that for each scenario the distance covered by almost 85% and 50% of passengers has been evaluated.

The results of the extended risk analysis methodology application to the reference scenario are reported in Figure 5:

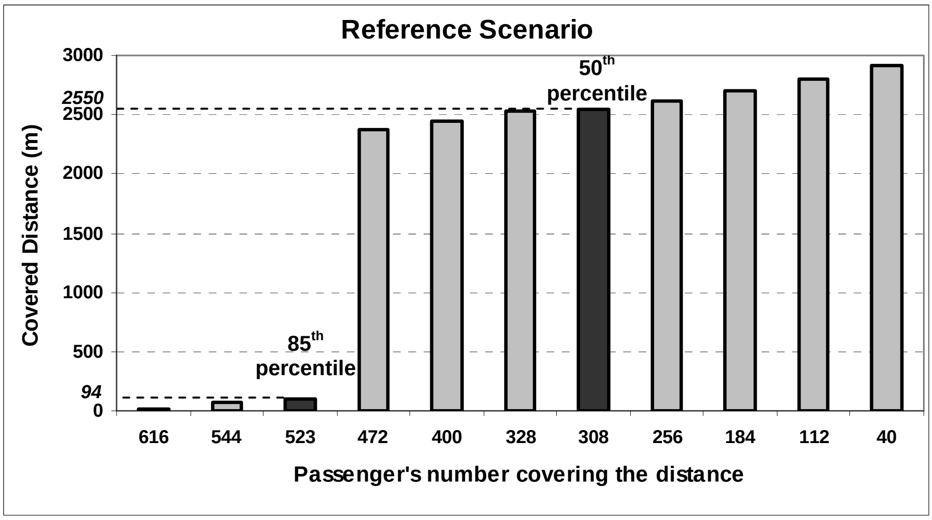

Figure 5: Reference scenario expected covered distances

Figure 5 shows that, in the reference scenario, almost half passengers cover a distance of approx 2550 m before lost consciousness, but the last 15% passengers to leave the train walk for less than 94 m. This is due to the double killing conditions considered, passengers nearer to fire event are reached by a life incompatible heat condition so early that they couldn't start evacuation procedures; moreover other passengers are reached by toxic gasses in a so high concentration that they fall unconscious.

3.2 Sensitivity analysis

The parameters investigated with the sensitivity analysis are those that better characterize the fire, the infrastructure and the toxic emissions. The sensitivity analysis has been conducted both to analyze the influence of some manageable parameters, such as tunnel section, air speed and heat release rate on accident severity, and of unknown parameters such as emission quantities, the effective heat release and the heat stoichiometric coefficient. This analysis fixes also the most important parameters to be studied in order to apply the risk analysis, factors with a low influence on the results could be assumed by bibliographical studies instead of those having a high influence that need to be defined with the most possible accuracy.

The sensitivity analysis has been conducted evaluating the percentage difference on the 85th and 50th percentile passenger's covered distance due to a 10% increment or decrement of each parameter.

Three groups of elements have been investigated: the first one (*fire design*) is the most important for vehicle and infrastructure designers whose choices can influence those parameters, the second one (*environment characteristics*) is mainly devoted to the infrastructural point of view and the third (*toxic smoke emissions*) interests material engineers that have to reduce toxic emissions due to seats, tents and facing combustion characteristics.

In Figure 6 and Figure 7 the effects of fire design, environment characteristics and toxic smoke emissions on passenger's covered distance are showed through two different parameters, that are respectively the 50th and the 85th percentile.

In Figure 6 can be seen that four parameters influence the distance of more than 10%, three has a low influence equal or less than 5% and the other three has substantially no influence.

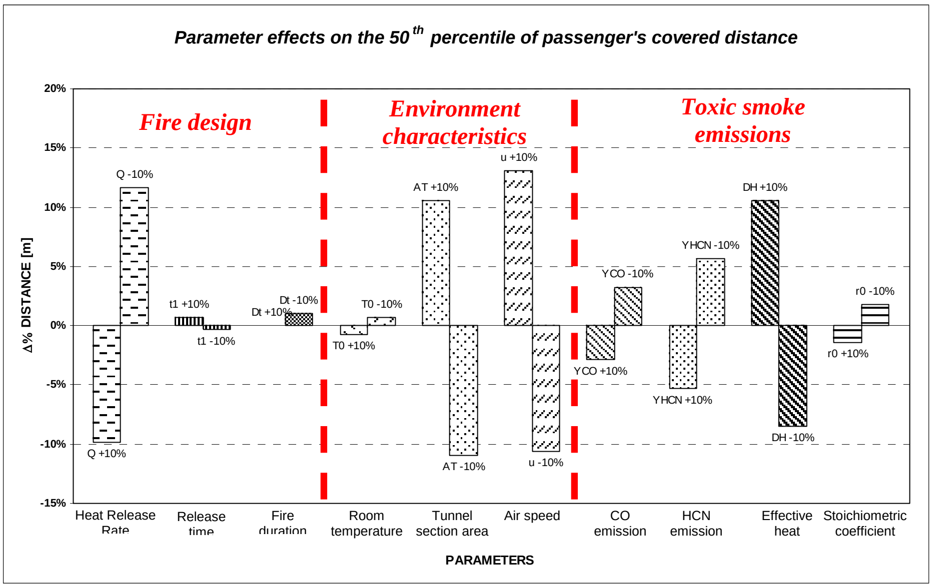

Figure 6: Parameter effects on the 50th percentile of passenger's covered distance

The results contained in Figure 6 shows how fire design has an influence only thought the HRR, increasing this parameter a sensible reduction of the covered distance has been registered. Infrastructure characteristics highly influence the results trough two different parameters that are: tunnel transversal section area and air speed. Increasing the tunnel section the smokes will be more diluted, so their toxic effects will be less consistent; the second one is the parameter with the higher effect, an increasing of air speed of 10% cause an increment of the covered distance of about 13%. This result could be unexpected, but it must be considered that fire design is fixed and so air speed has an influence on smoke dilution and not on heat release rate. The reference scenario considered in this study doesn't consider artificial meccanical ventilation and fixes fire power so an air speed increase has only the effect to increase smoke dilution. This analysis shows the importance to consider, during tunnel design, the effects of tunnel section area and the importance of evaluating the possibilities of normal ventilation which characterize each tunnel.

Finally, the last highly influencing parameter, is the effective heat release by a kilogram of combustible; this is a material characteristic and its importance must be a stimulus to study in depth train materials behavior. The reason why a heat release growth has a benefic effect are due to have considered a fixed HRR in fact this condition cause that the same HRR is reached with a smaller fire and so with less toxic emissions.

In Figure 7 the results of the same sensitivity analysis conducted on the 85th percentile of passenger's covered distance are reported. It shows how the variation of three parameters has a huge influence on the covered distance, otherwise five parameters has no influence at all. This is due to the fact that these parameters have an influence only on toxic gasses concentration and the first 15% passengers fell alive by heat effects, so they aren't influenced by different air composition.

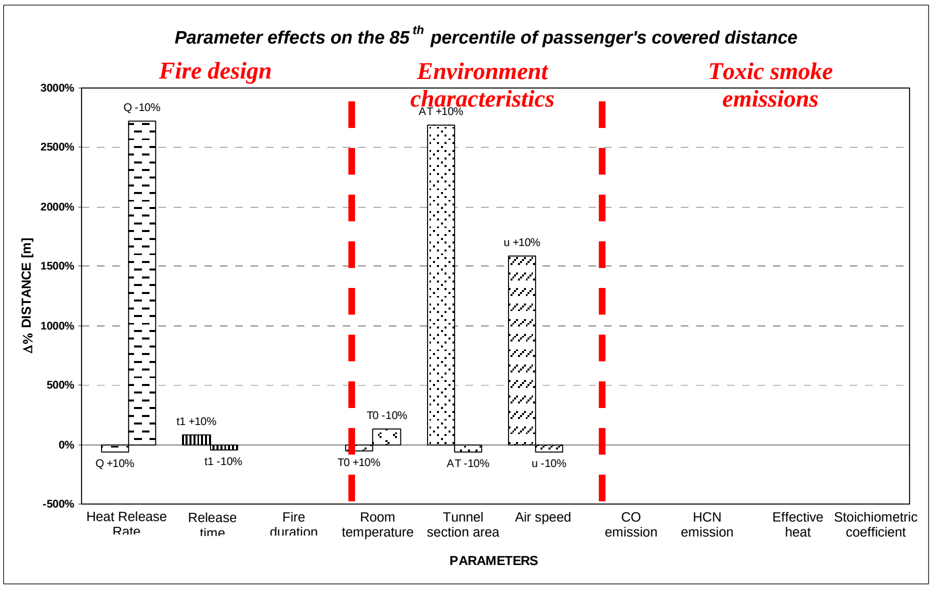

Figure 7: Parameter effects on the 85th percentile of passenger's covered distance

The results proposed in Figure 7 mainly confirm those showed in Figure 6 and referred to 50th percentile covered distances. Two parameters have a huge effect on evacuation chances and they are heat release rate and tunnel section; an increment of air speed inside tunnel has a benefic effect too. A 10% increment on tunnel section cause an increment on covered distance of more than 2500%. As shown in Figure 5 the passengers covering the 85th distance percentile are in a border condition in fact they fell die due to heat convection but a small better situation allow them to start walking, covering a long distance before falling unconscious as an effect of toxic smokes.

Sensitivity analysis show the great importance of infrastructure design and particularly of tunnel section design, in fact it has a huge effect on smokes stratification that are directly connected with passenger's evacuation chances. Other important infrastructure characteristics are safety measures provided inside tunnels such as refuges, by-passes (in case of double tube tunnel) or emergency exits.

4. EFFECTS OF TUNNEL SECTION

The extended risk analysis has been applied to different tunnel section in order to point out the infrastructure influence on covered distances and on passenger's saving likelihood.

The choice of the tunnel sections to be evaluated has been done with the goal of obtaining a good representation of Italian railway network. Three different possibilities has been considered:

- single track section (approx: 42 m^2);
- double track section (approx: 74 m^2);
- double track high speed section (approx: 91 m^2).

The "RFI S.p.A." standard section has been considered in all this three cases.

The single track section is characterized by two footpaths so evacuation procedures are considered to take place on both sides.

The result's comparison of these scenarios well identify the tunnel section effects on passengers covered distance. The sensitivity analysis has shown an high influence of tunnel section area on covered distance, this is confirmed by data reported in Figure 8.

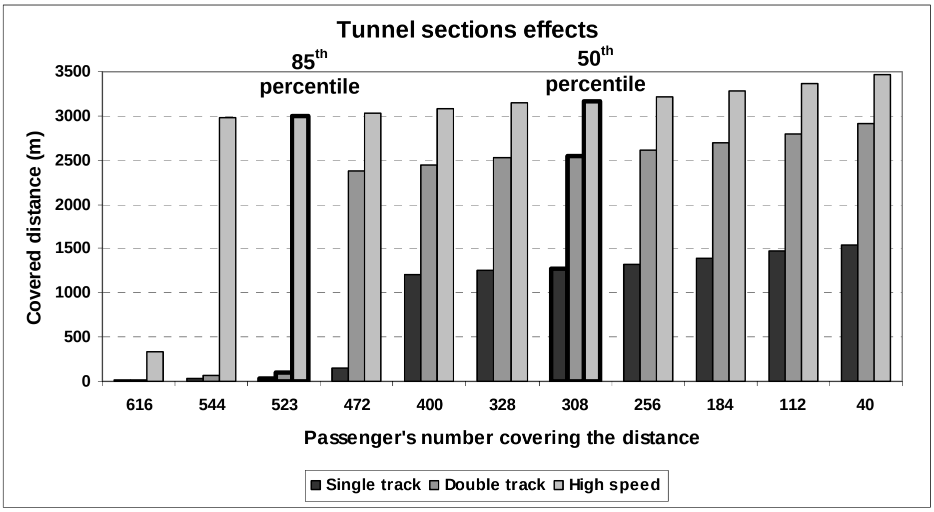

Figure 8: Tunnel sections comparison

Considering the distance covered by passengers 50% it can be seen that in a single track tunnel the distance is 60% lower than in a high speed one. In life rescue terms it means the necessity to have a refuge or an exit every 1200 m instead of 3100 m to save at lest half passengers as shown in Table 3. According to the Italian standard a carriageable exit every 4000 m must be provided [D.M. 28/10/2005], a comparison between this value and those contained in Table 1 shows that, in single track tunnels, all passengers have great difficulties to reach an exit, in fact the maximum covered distance is 1542 m. The worst case is the train stopped near an exit and passengers evacuating in the opposite direction. In this case the distance to be covered could be higher than the maximum value registered in any scenario; this could suggest a reflection about the necessity to provide safety refuges or exits, also not carriageable, at a distance lower than the one proposed by the Italian standard [3].

Table 3: Covered distance for different tunnel sections

Passengers number	Passengers percentage	Single track	Double track	High speed
616	100%	11	11	334
544	88%	33	64	2980
523	**85%**	**33**	**94**	**2992**
472	77%	147	2377	3034
400	65%	1209	2449	3088
328	53%	1263	2530	3142
308	**50%**	**1269**	**2550**	**3162**
256	42%	1326	2620	3214
184	30%	1398	2701	3277
112	18%	1470	2800	3367
40	6%	1542	2917	3466

The main effect of increased tunnel section area is the higher number of passengers who start the evacuation instead of the one obtained in the single track tunnel scenario. Table 3 shows how, in a single track tunnel, passengers coming out from the three doors nearer to fire couldn't start to evacuate, instead of those coming out from the two nearest doors in a double track tunnel and from the first door in a high speed tunnel.

These results point out the great importance of safety thresholds particularly for single track tunnels, mainly it could be useful to study better evacuation procedures and sensors to reduce detection time in order to increase life expectancy during a fire event.

5. INFLUENCE OF CENTRAL FOTHPATH IN DOUBLE TRACK SECTIONS

Table 3 shows how fire event conditions could be too severe for many passengers who could not be able to reach exits. In paragraph 4 out the importance to introduce exits or refuges nearer than the distance proposed by the Italian standard has been pointed. Another infrastructure improvement able to increase passenger's saving likelihood is the footpath between tracks: this is a solution less expensive than exits or refuges, but with a great impact on passenger's covered distances.

The distance between track allowed by Italian standards is 4 m, so the distance between sleepers is about 1.7 m and this allow to realize a footpath of about one meter. The central footpath installation allows to introduce a different evacuation model characterized by exits on both train sides as the one showed in Figure 9.

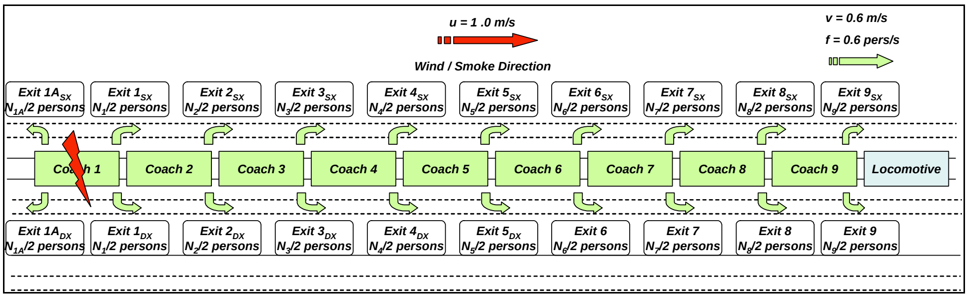

Figure 9: Both sides evacuation procedure

Considering the reference scenario, which results are showed in Figure 5, the two different procedures have been applied and the results are reported in Table 4:

Table 4: Evacuation procedures comparison

DISTANCES	**EVACUATION MODELS**	
	Standard procedure	***Two sides procedure***
D_1 [m]	11	2496
D_2 [m]	64	2550
D_3 [m]	2377	2595
D_4 [m]	2449	2649
D_5 [m]	2530	2703
D_6 [m]	2620	2757
D_7 [m]	2701	2820
D_8 [m]	2800	2892
D_9 [m]	2917	2955
D_{MAX} [m]	2917	2955
D_{MIN} [m]	11	2496

Each single row of Table 4 contains the minimum distance covered by passengers exiting the door indicated in the first column. The last two rows summarized the minimum and the maximum covered distance.

Data proposed in Table 4 pointed out the importance of evacuation procedures, particularly it shows the great impact of the footpath between tracks, in fact this infrastructure improvement increase the minimum covered distance of more than 2450 m allowing all passengers to have a great chance to reach an exit.

6. CONCLUSIONS

An extended risk analysis methodology has been applied to estimate the saving people likelihood and the number of expected deaths as a function of the distances covered by each passenger depending on different accident scenarios.

A sensitivity analysis has been conducted in order to identify the influence of main parameters on passengers evacuation capacity and to show the different input parameters importance. Four parameters having a great influence on the results have been identified and some useful indications for infrastructure and vehicle designers has been pointed out.

Comparisons between three different tunnel sections have been conducted and show how, as expected, most severe conditions have been registered for the smallest tunnel section as an effect of higher smoke concentration.

The effects of a footpath between tracks installation have been evaluated, the improvement in terms of passenger’s covered distance is appreciable, in fact in the scenario considered all passengers are able to cover a distance higher than about 2500 m that probably allow them to reach refuges or exits.

This study pointed out the importance of a risk analysis that must be conducted to obtain useful information on vehicle and infrastructure design. As proposed by the Italian standard an extended risk analysis seems to be requested especially for existing tunnels in order to get information on the best countermeasures to increase passengers fire safety conditions.

ENDNOTES

[1] These data are referred to the last five years of R.F.I. Florence Compartment.

[2] U.I.C. accidents are those characterized by property damages higher than 10’000 € or injuries with more than 14 days prognosis.

[3] According to the Italian standard a carriageable exit every 4000 m must be provided [D.M. 28/10/2005]

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