Methodological approach to reduce train accidents through a probabilistic assessment

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***Abstract*— In most situations, human and machines are linked in one system and accidents occur in most of them; but, there are no systematic procedures for reporting them. The present work is focused on developing a more scientific methodological approach which applies to reduce train accidents and in particular to improve safety in railway tunnels. The aim of our work is the development of a methodological approach through a probabilistic assessment in order to ensure the safety of users, staff and the emergency services in railway tunnels. We propose a real case concerning the safety of an Italian typical railway tunnel according to Ministerial Decree October 28, 2005.**

Keyword- Risk analysis, Railways, Safety

I. INTRODUCTION

After serious accidents, which happened in tunnels in the last few years, most countries have established new measures in order to evaluate the safety of existing tunnels and to establish new safety measures. Particular attention should be turned on related safety aspects [1]. So, in the late eighties and early nineties of the last century, European national governments as well the EU Commission decided to introduce competitive elements into the European railway industries [2].

Railways have unique characteristics that result in potential risks: heavy vehicles run at considerable speed over fixed rails while braking capacity is small due to minimal friction between metal wheels and rails. These characteristics generally prevent that trains can be brought to a standstill within the distance that can safely be observed by the driver and neither is a driver able to steer away to avoid conflicts. Therefore, railway networks are equipped with safety systems for excluding risks of derailments (by e.g. a broken rail, open movable bridge, unlocked switch), collisions between trains, collisions between trains and road vehicles on level-crossings, and accidents with maintenance workers [3].

The main interface between the safety system and the trains are the trackside signals which can be partitioned into automatic and controlled signals. Train separation on open tracks is guarded by automatic block systems in conjunction with automatic train protection. Block signals protect block sections and operate completely automatically based on train detection and interlinked signals. Block systems are complemented by train protection systems to further avoid human errors or failure (of the train driver). Signals also protect routes through station layouts to avoid head-on, end-on, and flank collisions.

These signals are controlled by dispatchers and the interlocking system. Safety and signalling systems rely on train detection systems for track occupancy and track-free detection. In addition, 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 [4], [5] such as pre-evacuation times (e.g. people may show vehicle attachment), occupant–occupant and occupant–fire interactions [6], herding behaviour and exit selection. In this context, several Computational Modelling software packages have been used in recent years as a tool for analysing occupant safety conditions in case of emergency.

Based on a real case study, a methodological approach to reduce train accidents through probabilistic assessment is presented in this paper. It is clear that there are many strategies for managing safety [7], [8].

We will focus on risk analysis for typical railway tunnel based on: Preliminary analysis of the risks and hazards; Identification of accrued initiators of accidents; Development of accident sequences (Fault Tree Analysis); Calculation of the level of risk.

The paper is divided in Section II in which we describe general description of the railway tunnel; Section III we analyse minimum safety requirements in railway tunnels and risk analysis process adopted and finally section IV in which we describe results of the study.

II. THE SCENARIO: GENERAL DESCRIPTION OF THE RAILWAY TUNNEL

In the literature two main categories of risk assessment methods can be distinguished [9]:

- *Deterministic safety assessment*: The consequences for loss of life of tunnel users and tunnel structure are analyzed and assessed for possible accidents that can occur in a tunnel,
- *Probabilistic safety assessment*: The consequences for loss of life of tunnel users and tunnel structure and the frequency per year that these consequences will occur are analyzed.

Consequences and the frequency of the consequences are multiplied and presented in risk for the individual tunnel user, a societal risk and a risk for tunnel damage. The tunnels object of the study put into practice the maximum number of measures for obtaining the highest security objectives. The railway tunnel is located on is South Italy. It is a double-track tunnel pipe, whose binary equivalent (sea side) is normally in the path towards the South-North and the odd track (side mount) is normally in the path towards North-South (Figure 1).

Fig. 1. Planimetry

The section has an open area of 48 m^2, with a distance between the rails of 3.56 m. The shape of the tunnel is of type F, with arched structure inverted from km 135 +103 to km 139 +579. In the railway tunnel there are:

- Niches hospital staff = n° 175 (each 25.50 m),
- Large niches (11 m^2) railway track odd = n° 6,
- Large niches (11 m^2) railway track even = n° 6,
- Railway link (48 m^2) = n° 2,
- railway link (730 m^2) railway track even = n° 1 (communicating with the outside).

The following figure (figure 2) shows the layout of our railway tunnel.

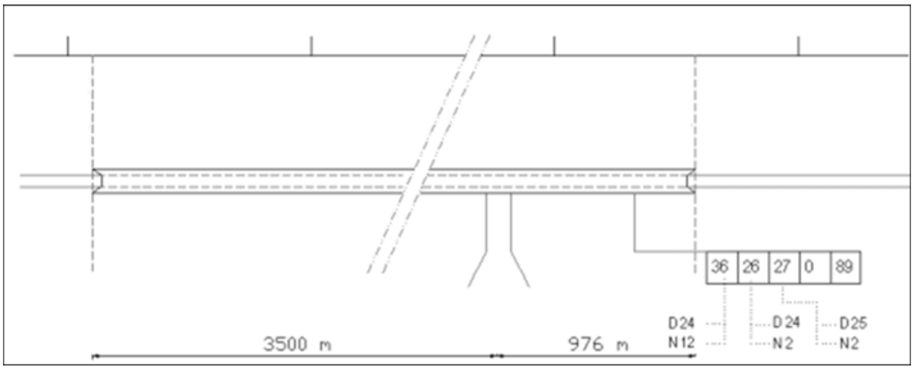

Fig. 2. Layout of the tunnel

Risk analysis was developed considering the train traffic expected in 2021. The following table (Table 1) shows the data of daily traffic expected for 2021, with the distribution day/night according to the type of train. The values in the table refer to the sum of trains on two tracks.

TABLE I
The train traffic expected in 2021

Train traffic expected in 2021													
Traffic 24h				By Day				By Night				Total	
LD	REG	F	Fhaz	LD	REG	F	Fhaz	LD	REG	F	Fhaz	By Daily	By Night
28	26	13	3	24	26	6	1	4	0	7	2	57	13
Legend: LD = long-distance; REG = regional; F = freight train; Fhaz = train hazardous substances													

III. MINIMUM SAFETY REQUIREMENTS IN RAILWAY TUNNELS AND RISK ANALYSIS PROCESS

The aim of our study is to develop a methodological approach in order to assess the acceptability level of the risk associated with the operation of a typical railway tunnel according to the requirements of the law [10]. In this paragraph we analyse the minimum safety requirements for railways tunnels and risk analysis process adopted. The tunnel, object of our study, is equipped with the following minimum infrastructures:

- Exit,
- Smoke control system,
- Emergency telephone system,
- Emergency zone,
- Access roads,
- Radiopropagation system,
- Availability of electrical power,
- Measures of fire protection,
- Emergency lighting,
- First aid equipment on board,
- Training of staff.

Here below in figure 3 is reported a scheme of systems installed.

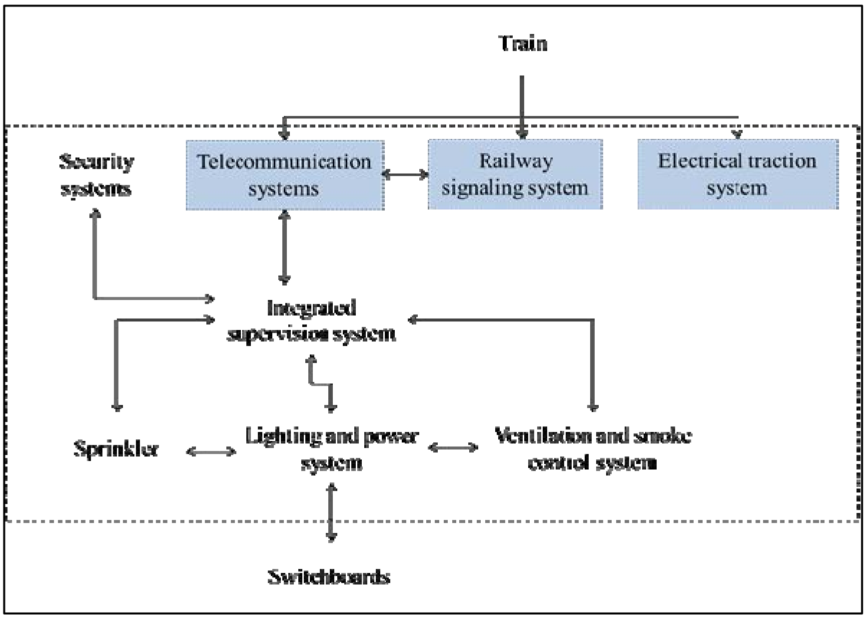

Fig. 3. Systems installed

In figure 4 is shown methodological approach adopted.

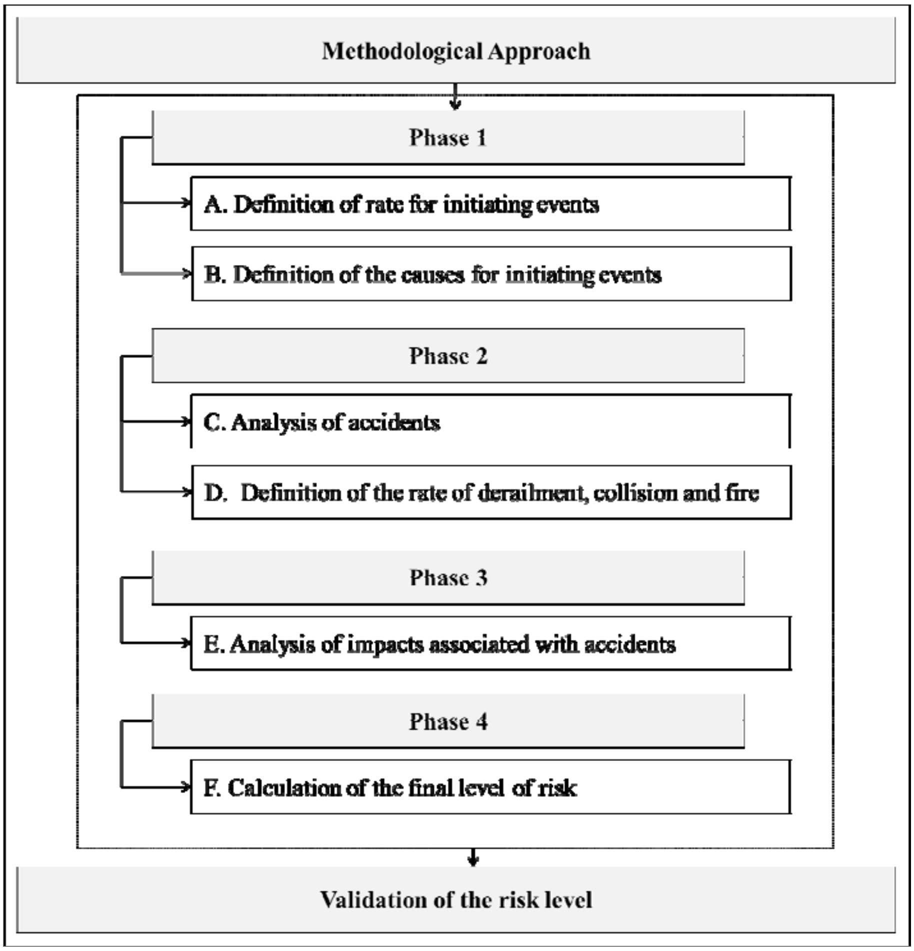

Fig. 4. Methodological approach

A. Phase 1 - Definition of rate for initiating events

For each event following steps were adopted:

- Assessment of the statistic data to be used,
- Critical interpretation of the data,
- Evaluation of the accidents trend by applying regression models,
- Estimation of uncertainty.

For the data analysis we have considered a period from 1995 to 2010.

B. Phase 1- Definition of the causes for initiating events

The study is based on the assessment of fault tree analysis. Below are presented primary causes and secondary causes characterizing a typical train accident:

- *Human erro*r such as Personnel on board, Other staff;
- *Technical causes* such as infrastructure (armament, signaling systems, other structures - including civil works);
- *Railway equipment* such as railway engine, freight wagons, traction system and braking system;
- *External causes* to the railway system such as environmental causes, lack of accountability of users - people outside.

In figure 5 is shown an example of Fault Tree Analysis.

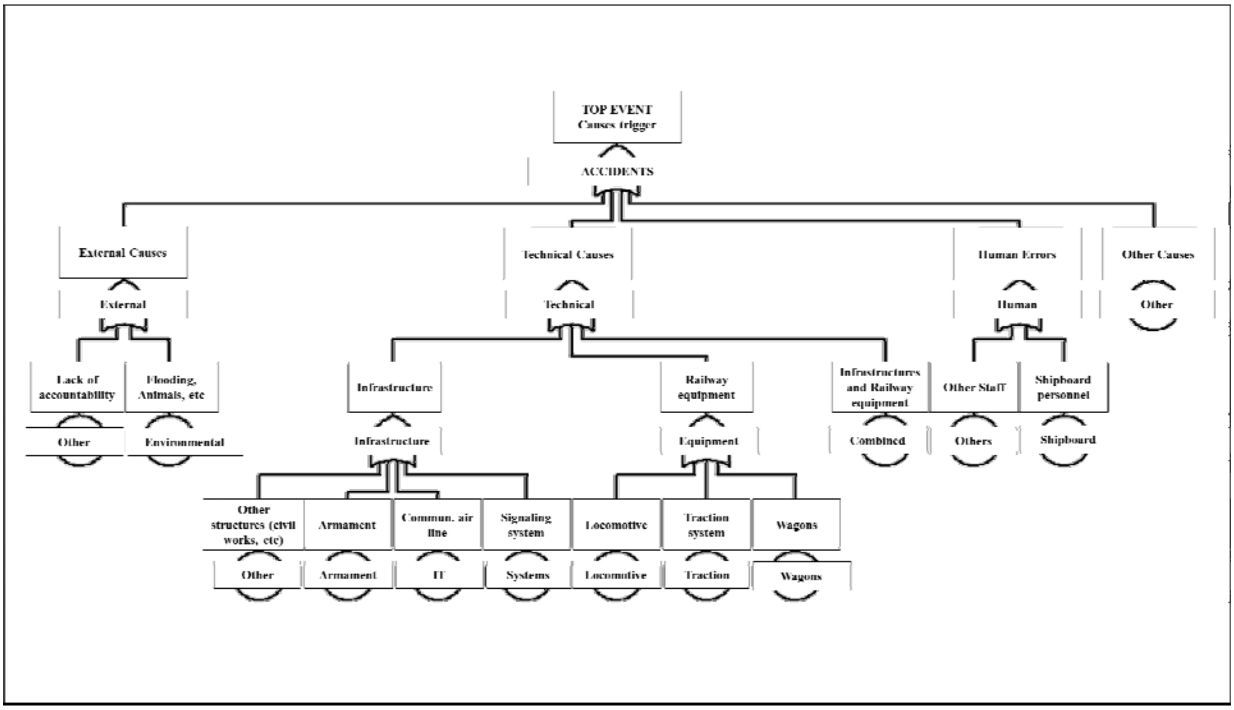

Fig. 5. Fault Tree Analysis

In Table 2 is shown an example of analysis for the main derailment causes.

TABLE II
Derailment causes

Derailment causes				
Type of train:	**Passenger train**	**Goods trains**	**Not Specified**	**Normalized Value**
Human Error				
Failure or incorrect compliance with the regulations	10	13	3	0,34
Failure or incorrect compliance with the requirements movement/ techniques	2	3	0	0,07
Irregular movements of maneuver	7	30	2	0,51
Failure of the stop signal	1	3	0	0,05
Incorrect preparation of itinerary/routing	1	0	0	0,01
Exceeding speed limit	2	0	0	0,03
Staff not attentive	0	0	0	0,00
Technical Errors				
Infrastructure				
Irregularities in the infrastructure (track / catch / portals)	6	1	2	0,33
The track geometry irregularities (bumps / rail route) or headquarters / infrastructure	9	9	0	0,67
Train, locomotives, passenger coaches, etc				
Defective or worn mechanical / electrical	3	10	0	0,48
Containers / containers / tanks circulating iron with defects in the structures or components	0	2	0	0,08
Hotbox	1	0	0	0,03
Load non-compliant (displaced / excessive weight / sore broken)	0	5	0	0,19
Loss of components	2	3	0	0,19
Breaking the coupling means	0	1	0	0,03
Causes external to the rail system				
Landslide / boulders / trees bulky	1	0	0	0,06
Abnormalities for external event	6	4	0	0,67
Vandalism	1	0	1	0,14
Abnormalities on the teams / work sites	1	0	1	0,14
Other causes				
Obstacles	1	0	0	1,00
Not determined causes				
	0	9	1	1,00

C. *Phase 2 - Analysis of accidents*

In order to have an estimate for risk analysis, for each event initiator was performed the following analysis [11], [12]:

- Assessment of the statistic data to be used,
- Analysis of the quality of the statistic data,
- Estimation of potential trend for accidents,

We have defined the uncertainty following equation 1:

$$I_C = \sum_{i=1}^{n} \frac{t_i - T_i}{T_i} \qquad (1)$$

where:

Ic = uncertainty of the ratio, expressed as a percentage (absolute value)

ti = the value of the real rate reported for a given year

Ti = value of the rate calculated according to the exponential curve interpolating

n = number of data (ie rates) used for the calculation of the rate.

In Figure 6 is shown data for accidents in circulation.

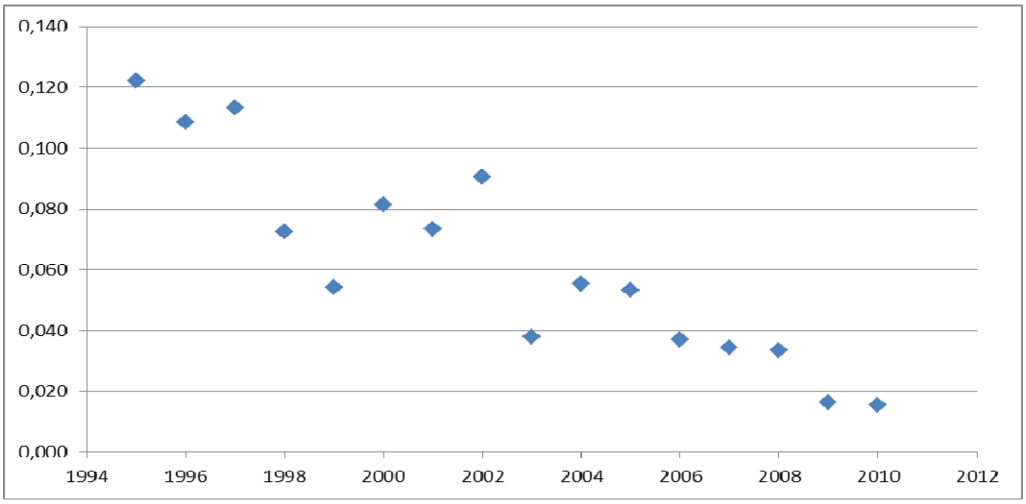

Fig. 6. Accidents in circulation (normalized value)

D. Phase 2 - Definition of the rate of derailment, collision and fire

In this phase we defined the rate for derailment, collision and fire. In Table 3 is shown the rate of derailment

TABLE III
Rate of derailment (1995-2010)

Year	**Passenger train (1)**	**Freight train (2)**	**Rate of derailment for (1) (events/train-km) Normalized Value**	**Rate of derailment for (2) (events/train-km) Normalized Value**
1995	5	16	0,043	0,043
1996	8	9	0,069	0,025
1997	7	16	0,061	0,043
1998	4	10	0,035	0,028
1999	1	7	0,089	0,022
2000	7	8	0,062	0,025
2001	3	8	0,026	0,024
2002	7	2	0,061	0,060
2003	0	1	0,000	0,032
2004	5	7	0,043	0,021
2005	2	4	0,169	0,127
2006	4	6	0,033	0,185
2007	4	4	0,033	0,129
2008	3	5	0,025	0,178
2009	1	4	0,084	0,021
2010	2	1	0,168	0,037

In a similar way were calculated values for collision and fire.

E. Phase 3 - Analysis of impacts associated with accidents

The estimation of the consequences, is based on “models of lethality” or in other words for each initiating event (derailment, collision, fire), the models estimate the expected number of fatalities by adopting a probabilistic approach that incorporates the deterministic data available [13], [14], [15]. In Figure 7 is shown a typical tree passenger train derailment.

Derailment – passenger train [event/year	Derailment with fatality		
2,54E-04			Frequency
	0,109		2,77E-05
	0,891		2,26E-04

Fig. 7. Example of tree passenger train derailment

F. *Phase 4 - Calculation of the final level of risk*

The objective of this phase is to calculate the level of risk associated to the gallery object of study, according to the results described in the previous phases.

The level of risk expected, IR, in the gallery object of our study was calculated to be 4,00•10-11 fatality/(passenger-km-year). The risk level of individual stands within the area of attention (Figure 8), so according to Ministerial Decree October 28, 2005 it is necessary to carry out assessment like ALARP evaluations, "As Low As Reasonably Practicable" on the curve of cumulative hazard.

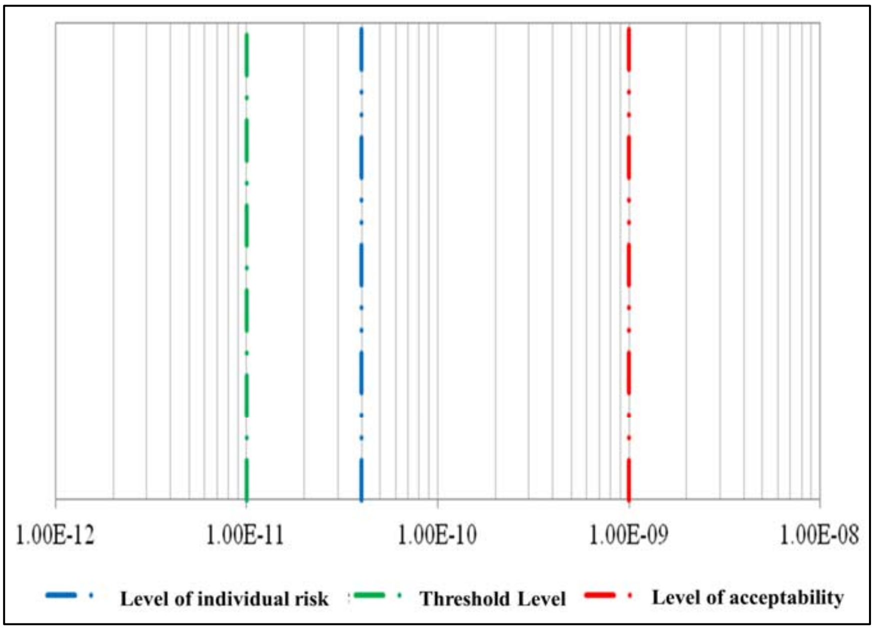

Fig. 8. Level of risk expected

As is shown in Figure 9 the curve of the Cumulative Risk is within the ALARP area.

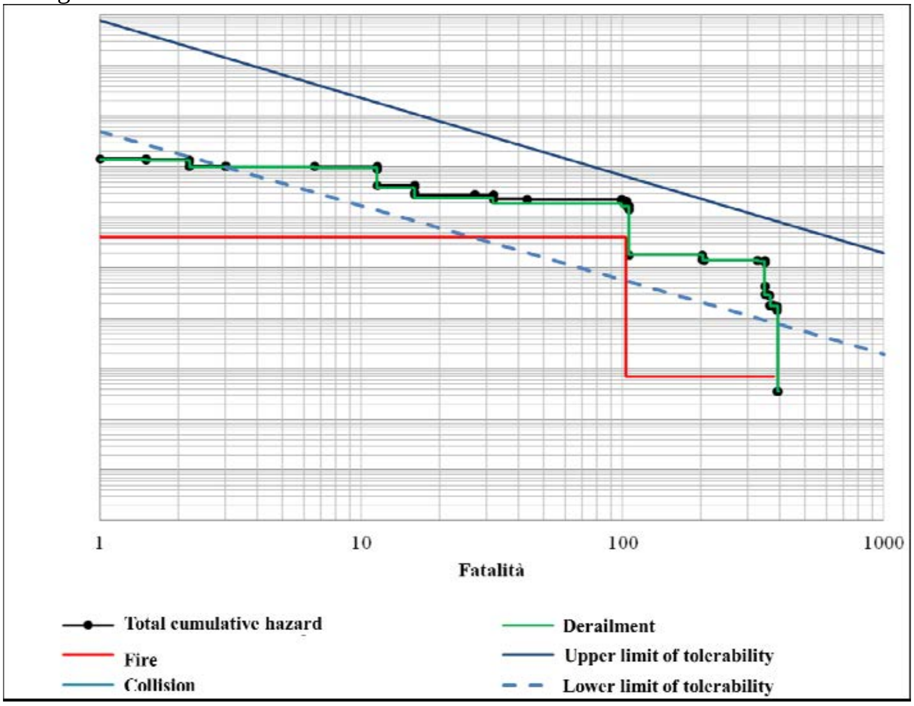

Fig. 9. Total cumulative hazard

IV. CONCLUSION

The main results of this study showed that the level of railway safety in Italy has greatly improved. The methodological approach adopted is simple in the sense that it include simple tools and it able to consider several parameters in order to simulate the complexity of the system object of the study.

We would like to observe that a critical role in this kind of system is due to human factors. Human abilities and limitations are manifested in their performance of mission tasks. Since humans are essential to the operation of such system, it is important to measure the effect of human performance on the system reliability.

There is evidence that the human component is responsible for 20-90% of the failures in many systems depending upon degree of human involvement in the system. Human factors specialists usually provide only qualitative analysis of human factors in human machine systems. A better approach to study human factors in system effectiveness is to combine the human and hardware performance measures into a meaningful index taking into account the interaction of human and hardware components of the system.

From this point of view a safety training based on scientific approach such as Behavior-based Safety (BBS) could improve organizational safety culture. By increasing the quality and frequency of safety feedback in the organization, barriers between employees both within and across organizational levels are reduced. Improving safety communication (both correcting and rewarding feedback) through BBS leads to a more open, positive, and trusting safety culture as well as improved safety performance.

We can conclude this work with following observations and considerations. Important for the selection of a tunnel safety assessment method is the level of detail in the available input for the method. Once the tunnel has been taken in operation an assessment of the safety performance is necessary periodically. In a periodic safety evaluation the following methods or tools could be used: Checklists; Casuistry: for existing tunnels during operation all serious accidents should be evaluated. Inspections; Audits.

The implementation of safety management systems guarantee safety work more organised and enhanced preventive safety work in order to recognise safety risks before they lead to accidents.

Future developments will concern the development of models of reliability in order to obtain the main parameters of reliability (MTBCF), maintainability (MTTR) and availability (intrinsic and operational) for the railway tunnel object of the study

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