Fire protection of emergency electrical devices: effect on the level of risk – a case study of a rail tunnel

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Abstract

The paper proposes the main results obtained from the Quantitative Risk Analysis developed on an existing tunnel, according to the Ministerial Decree "Safety of Railway Tunnels" (October 28th 2005).

The fire produces the most severe scenario among the possible emergencies in confined area, thus the regulations in Europe and in Italy (Technical Specifications for Interoperability, Decision December 20th 2007, Ministerial Decree October 28th 2005) obligate to direct adoption of measures and devices for prevention and protection to reduce the probability of occurrence of this specific critical scenario and the containment of the fire effects.

To mitigate the damage, the difficulty of providing an effective external rescue in a short time involves supplementary safety measures aimed at improving the process of self-rescue.

Keywords: fire safety engineering, emergency lighting, rail tunnel, safety electrical system, quantitative risk analysis.

1 Introduction

In rail and road tunnels the occurrence of fire is the most dangerous scenario in terms of resulting emergencies [1].

Therefore, the best practice and current regulations require measures and devices for prevention and protection, designed to reduce the probability of occurrence of fire (critical scenario) in tunnel and to control the effects in case of its occurrence [2].

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In order to mitigate the damage, the difficulty of providing an effective external rescue in a short time involves supplementary safety measures aimed at facilitating the process of self-rescue activated as consequence of the fire scenario.

Accordingly, the safety electrical system, which supplies the emergency lighting and, where provided, also the internally illuminated exit signs, must be protected by faults, as far as possible, ensuring high reliability in case of impact/fire.

The case study shows the results of quantitative risk analysis developed for the specific risk assessment of a rail tunnel located in Italy and subject to the Decree “Safety of railway tunnels” (October 28th 2005). Current analysis and the resulting project were aimed at verifying the primary importance of the reliability of the safety electrical installations. Defining the infrastructural conditions of the tunnel, the performance of safety devices that influence the risk level of the system, was found to be the main safety parameter.

Derived observations are essentially suitable to all cases of collective transport systems in underground and they suggest a useful indication also for the case of road tunnels (that differ from rail tunnels by physical characteristics of fire and number of people exposed).

The Quantitative Risk Analysis highlights the influence of the performance of safety devices, in particular of emergency lighting, on the risk profile characteristic of the tunnel system.

The availability of technical solutions, that ensure the certified reliability of the performance in case of fire, allows us to design high safety standards at extremely affordable costs, where the alternatives are analytically evaluated. Thus, in some cases (such as this case study) a “not adaptable” system becomes compliant with the safety expectations of the community, as required by specific technical standards.

1.1 Safety of rail tunnel: regulatory framework

The current regulations, relevant to the case of railway tunnels, are constituted by European Technical Specifications of Interoperability (TSI) and national regulations.

In particular, for the purpose of regulatory requirement, the specific rules are:

- Commission Decision, December 20th 2007 “Technical specification of interoperability relating to safety in railway tunnels in the trans-European conventional and high-speed rail system”
- Ministerial Decree “Safety of rail tunnels”, October 28th 2005 (Italian law)

Both sources require a specific approach for the safety compliance of existing infrastructure and for the new tunnels, through a system of prescriptive and performance requirements.

The Decision refers to the “not systemic” approach of performance: the single railway subsystems guarantee minimum performance levels. For some of them, the safety subsystems defined, the TSI relate to EN 50126 (RAMS approach in the railway system) with the specific Safety Integrity Level (SIL), that define acceptable rates of unreliability. However, the definition of safety subsystems is unclear, especially with regard to infrastructure devices (and therefore the Electromotive Force and Emergency Lighting in tunnel).

The Decree proposes both minimum safety requirements and quantitative risk analysis. This approach provides an integrated project. The safety level is measured by quantitative indicators: Individual Risk (IR), which proposes normalization of expected value of fatalities by the number of exposed and Societal Risk, which evaluates Back-Cumulated risk Distribution (BCD).

The design of tunnel meets the safety requirements imposed by the standard where the risk indicators take a value compliant with predefined thresholds of acceptability according to ALARP criterion (As Low As Reasonably Practicable). This approach allows the safety systemic design (also economically, with costs-benefits evaluation).

2 Subsystems electrical safety: minimum performance requirements

According to design of the safety systems the request of performance refers to criteria of good practice since a specific request of performance in terms of availability and reliability is not expected. For both the electrical (safety) devices and the emergency lighting systems the Decision requires that: "*Electrical installations relevant for safety (Fire detection, emergency lighting, emergency communication and any other system identified by the Infrastructure Manager or contracting entity as vital to the safety of passengers in the tunnel) shall be protected against damage arising from mechanical impact, heat or fire.*

The distribution system shall be designed to enable the system to tolerate unavoidable damage by (for example) energizing alternative links. The electrical supply shall be capable of full operation in the event of the loss of any one major element. Emergency lights and communication systems shall be provided with 90 minutes backup".

The Italian Decree defines the minimum performance required to the emergency lighting system: "*The electrical components for supply of emergency systems (lighting and power) must be protected from damage caused by failures and accidents.*

The installations of electric power supply must also provide suitable configurations or redundancy such as to ensure, in the event of single failure, the loss of short sections of the system, but not higher than 500 meters".

The safety devices should ensure the high fault protection (i.e. high reliability of components and appropriate redundancy of system) in usual operation, and the high reliability performance (durability in terms of exposure to fire, and protection against short-circuit due to failures) under fire conditions.

3 Case study

The evaluation of quantitative risk analysis is applied to railway tunnel (case study), whose geometric configuration, infrastructures and typical fire make it particularly difficult to verify the compliance with expected levels of safety. Thus, the comparative evaluation of alternative designs and traffic management is required.

The tunnel (see Figure 1) has a length of 2050 meters and complex infrastructural configuration: the end W consists of a subway station, to follow a first section (mono-directional tunnel) is about 250 meters in length (cross-section of about 26 m^2), then follow a room of about 100 meters and a section of about 1700 meters (mono-directional tunnel) on which an underground station is inserted. Actually the tunnel does not have an emergency lighting system.

The materials and solutions have not allowed a safety compliance configuration. Thus, innovative solutions in terms of safety management are necessary.

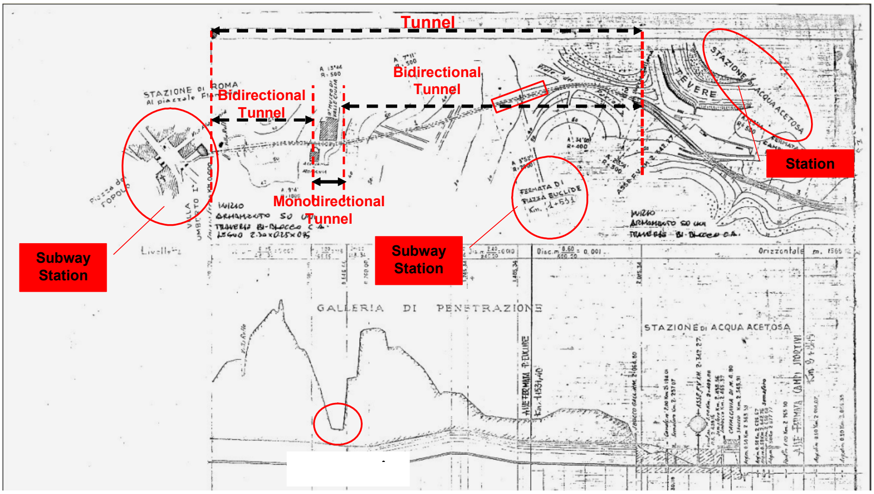

Figure 1: Layout of railway system.

The checking procedure, according to the Italian decree, highlights the need to adopt Extensive Risk Analysis (see Figure 2).

3.1 Systems safety design A

A platform that meets the minimum measures (0.5 m) of the Decree and an emergency lighting system were provided.

The compliance minimum design adopts a system of Electromotive Force and Emergency Lighting protected by a general fire, with cables compliant with the IEC 60331

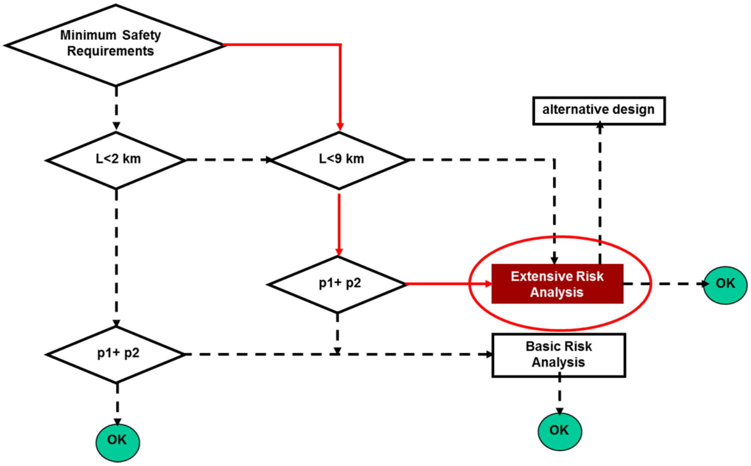

Figure 2: Checking procedure for safety evaluation of railway system.

3.2 Systems safety design B

According to the improved design, following the same geometric conditions of the infrastructure, the systems of Electromotive Force and Emergency Lighting show an enhanced fire performance as required by DIN 4102 and are able to keep thermal stresses higher than those foreseen by IEC 60331, especially for the wiring. All other conditions of the design A are unchanged.

4 Quantitative risk analysis: relevance of safety systems

The two described designs have been verified by developing a coupled process of simulation (fire and exodus). To determine the real conditions [5] of thermal and chemical harmfulness of exposed subjects and safety devices, a strategy of simulation in two steps was adopted [7]:

- Modelling of the rolling stock set up with the real materials that are characterized by chemical properties and simulation of the likely fire curve of the train (minimum ignition).
- The likely fire curve, derived from the small scale simulation, was compared with the experimental fire curve of Ingason [6] (see Figure 2)

This approach allows us to characterize the fire behaviour of the rolling stock in use in the tunnel, following two steps (fire and exodus) of simulation that return likely the actual conditions of hazard.

In large-scale simulation (simulation of fire to the train in tunnel and simulation of exodus) the relevant characteristics to the development of the

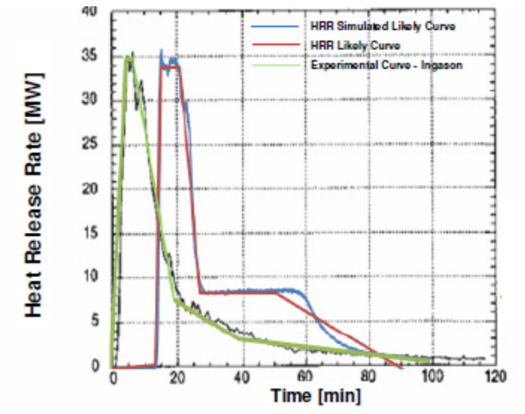

Figure 3: Comparative analysis of fire curves.

hazard [8, 9] were highlighted. To the same geometrical conditions of the tunnel, is:

- subsystem 1: availability, in the transient pre-flash over, of the electromotive force (emergency lighting system).
- subsystem 2: availability, in the transient pre-flash over, of emergency lighting (conditioned on the availability of the subsystem 1).
- subsystem 3: reliability, efficiency and effectiveness of emergency lighting in the transient post- flash over.

Considering the portion of electric backbone, that supplies the emergency lighting, and its (small) distance from the train (length of section about 5 meters), the system and the devices are subject to thermal stresses (T = 300°C) after 16 minutes from ignition.

Since the wiring is not protected from the fire there is a fast loss of system availability (250 meters of section) that results in the electric short circuit of device more thermally stressed.

5 Results

Figure 4 shows the trend of visibility (black line) less than 3 meters and the motion laws of exposed subjects in the case of Design A: the majority of exposed subjects are unable of self-rescue.

The solution of Design B, following the same conditions, leads to much better results (see Figure 5), since the expected duration of the devices performance is equal to about 46 minutes from the start of the emergency (30 minutes, according to the certification E30, from the start of thermal critical stress).

The traditional design (Design A) shows a deficit of safety, which is improved only by the expensive (and relatively not efficient) construction of a smoke extraction system, located in the room (fires localized in the first section of tunnel).

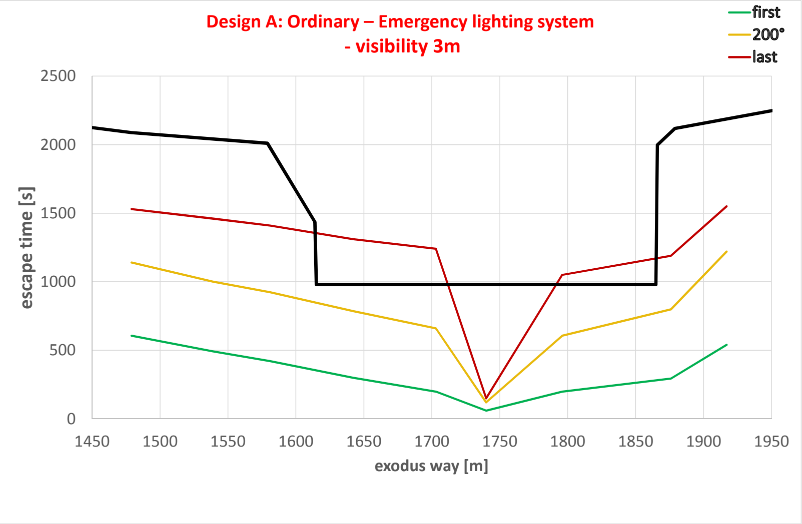

Figure 4: Motion law – visibility less than 3 m (Design A).

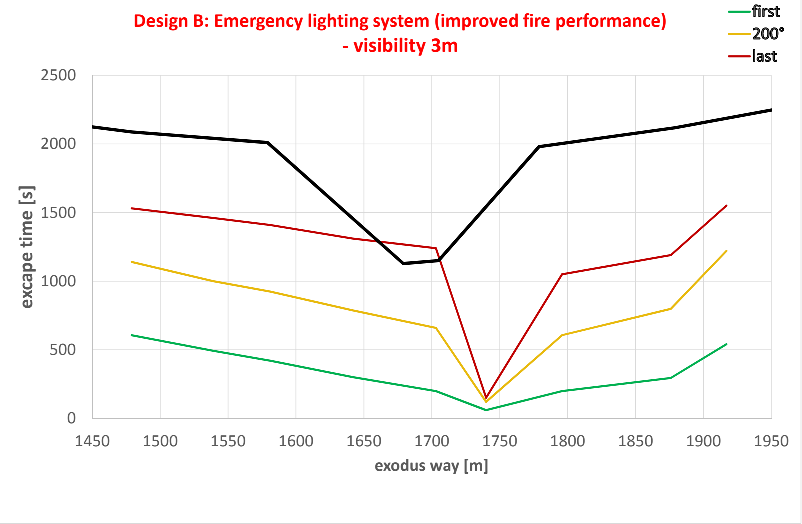

Figure 5: Motion law – visibility less than 3 m (Design B).

It is also required a radical decrease of the level of service and the replacement of the rolling stock. Thus the tunnel, according to results from the analysis, should be radically redesigned.

The number of fatalities associated with the solutions A and B is very different (as shown in Figure 6).

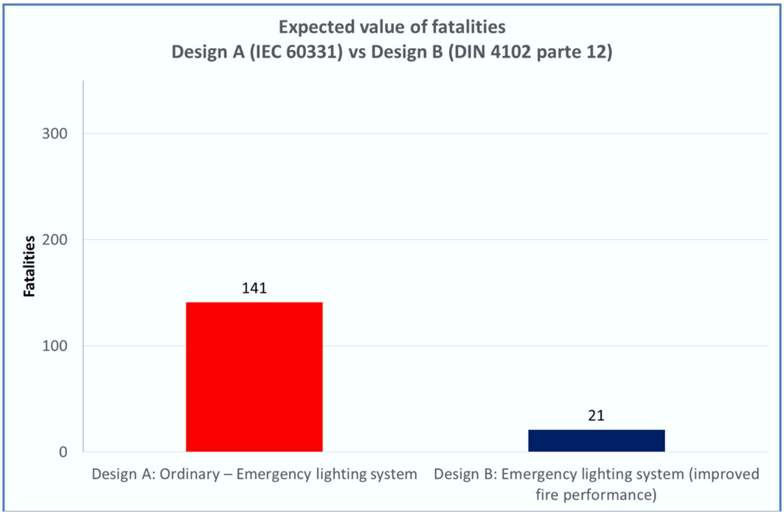

Figure 6: Expected value of fatalities (Design A vs. Design B).

Given other variables relevant to the process of self-rescue and to the emergency management, the study has developed all scenarios of the Event Tree Analysis, by obtaining the probability and the corresponding damage [3, 4].

The evaluation also allowed us to achieve the values of the risk indicators relating to both designs [10] (see Figures 7 and 8).

Based on these results a cost-benefit analysis (CBA) was also made, so check the equivalent cost-effectiveness of the system of wiring (see Table 1). The analysis requires the choice of a conventional economic value to life (evaluated at €1,500,000) as risk indicators refer to the number of fatalities.

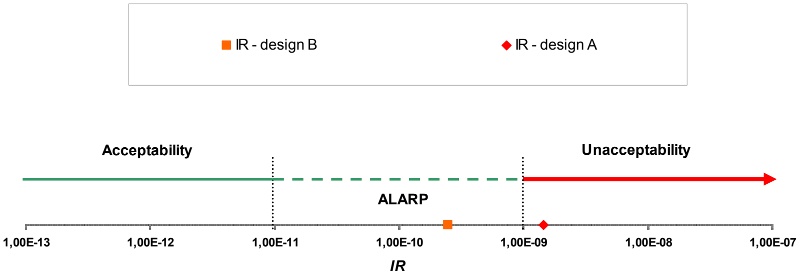

Figure 7: Individual risk indicator (Design A vs. Design B).

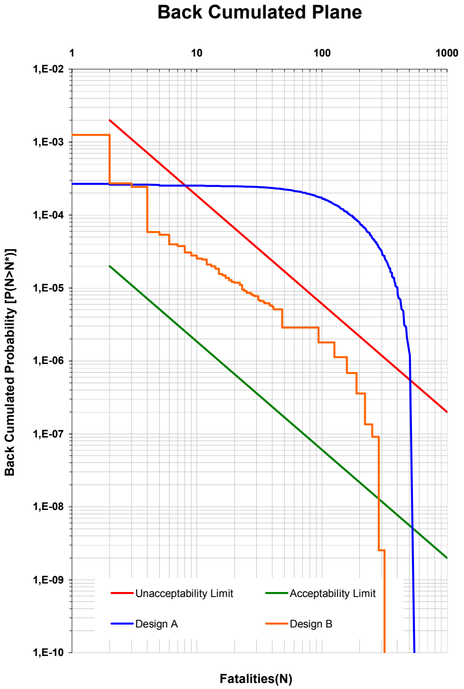

Figure 8: Societal risk – back cumulated distribution indicator (Design A vs. Design B).

The CBA applied to the devices, considering the amortization period of 25 years, returns a judgment of absolute convenience (see Table 1).

Table 1: Cost-benefit analysis (amortization period: 25 years).

Benefit - Cost Evaluation		
Estimated incremental cost	[€]	1.17E 05
Risk decrease (ΔR)	[F]	3.13E-03
Value of a life year	[€]	1.5E 06
Annual decrease	[€]	4.7E 03
Amortization	[Y]	25
Benefit	[€]	1.17E 05
BCE		ok

6 Conclusions

Quantitative Risk Analysis shows that the system performance of Electromotive Force and Emergency Lighting, under fixed conditions of emergency scenario, is the primary determiner of risk level relating to the fire events. The evidence of this result is clear if you take methods of analysis "expert and scientifically sustainable", by improving the traditional methodologies typical of the safety compliance analysis (ex NFPA 130 and Ministerial Decree 10/28/05).

The performance of safety devices (in particular, of emergency lighting) on the characteristic risk profile of the tunnel system are highlighted.

The availability of technical solutions ensures the certified reliability of the performance in case of fire.

High safety standards are obtained at extremely affordable costs.

The compliance with the safety expectations of the community, as required by specific technical, is verified.

In Italy, for both road and rail tunnels, safety targets that suggest safety requirements related to safety levels are fixed.

Operators must prove the achievements of the above safety targets by quantitative risk evaluation.

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