ROAD TUNNEL RISK-BASED SAFETY DESIGN METHODOLOGY BY GU@LARP QUANTUM RISK MODEL

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ABSTRACT

The ALARP concept is used in different countries for different sectors of activity where a risk assessment or measure is requested. In this paper a model is developed based upon ALARP principle for tunnel risk-based design in case of fire accident scenarios. In Italy, ALARP risk acceptability and tolerability criteria have been adopted then the compliance with them has to be verified in order to guarantee a minimum-sufficient level of safety. The quantum of risk coupled with any design scenario is defined and modelled and the consequent individual quantum of risk coupled with the single exposed unit in the scenario is defined too. The methodologies for the identification of the requested design scenario, in number and type, are outlined. The scenarios are described in a shape suitable as INPUTS in the thermo-dynamical numerical simulations for fire generation and exposed units evacuation. The expected OUTPUTS of the numerical simulation are the estimations of the number of the fatalities (N) coupled with the single specific scenarios. In parallel with the above physical deterministic scenario simulations, a conceptual and operational procedure has been also established for the scenarios probabilities assessment. Merging the resulting data of both the above separate models, the risk quanta Gu@larp model is finally established. A case study is developed considering scenarios related to a virtual limit tunnel to support the description of the model itself, properties, advantages and perspectives.

Keywords: Gu@larp, ALARP, risk quanta, risk-based design, risk acceptability, risk tolerability, risk line, fire-accident rate, expected fatalities, road tunnel safety.

1 INTRODUCTION

In this paper we developed a model based upon the ALARP principle for risk-based design for fire accident scenario in a tunnel compliant with the acceptability and tolerability criteria adopted in Italy in order to guarantee a minimum-sufficient level of safety. The methodologies for the identification of the requested design scenario, in number and type, are outlined. The major key factors for the scenario identification are enumerated as follows: (1) fire rate and fire design; (2) temporal and seasonal characteristics of the traffic; (3) location of the fire and people inside the tunnel; and (4) availability of performances of the protection systems.

Each one of the identified scenarios (S_i) is also coupled with the estimation of its probability of occurrence ($P(S_i)$) estimated with the parallel established procedure based on the tree diagram.

Each deterministic calculation ($N(S_i)$=number of fatalities in the S_i) provided by FDS simulator is our estimated value of the number of fatalities compared with the number of exposed units that are located within the distance of influence (potential damages) of the fire accident.

Merging the result data of both the above separate models, the risk quanta Gu@larp model [1], [2] is finally established.

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A case study is developed considering scenarios related to a virtual limit tunnel [2]–[5] to support the description of the model itself, the properties and advantages, and the perspectives.

2 SCENARIO IDENTIFICATION

Quantitative risk analysis has been carried out to identify and measure the quantum of risk of a unidirectional virtual tunnel having a length of 501 m and AADT of 7,500 vehicles per lane per day (two lanes). The focus of this paper are the risks created by fires occurring inside the tunnel that have the potential of causing injuries or fatalities to the persons inside the tunnel. The fire hazards and their consequences, as the number of fatalities ($N(S_i)$), are quantified for checking the requested compliance based on the estimation of the quantum of risk measure and not on the number of fatalities that is an unknown and not available information for direct estimation. In order to do this, in appropriate number of scenario types have to be identified and probabilized through the combination of the occurrence rate of a fire in a tunnel, the length of the tunnel, the traffic density, and finally the key factors that can influence the measure of the quantum of risk of a given scenario. But since an infinite number of scenarios can be derived from the combination of different conditions and factors, it is necessary to identify and select a limited number of scenarios that can be allowed to appropriately represent all possible scenarios. Once the fixed characteristic of the tunnel such as geometry (shape, slope, etc.) and structural materials are known, the major key factors in scenarios identification are:

1. Fire rate and fire design;
2. Temporal and seasonal characteristics of the traffic;
3. Location of the fire and people inside the tunnel;
4. Availability of performances of the protection systems =.

2.1 Fire rate and fire design

Fire inside the tunnel is most likely caused by collision and vehicle defect triggering fire. The occurrence of fire in a tunnel is very rare but, in any case, it needs to be investigated as it can develop into a critical event characterized by the speed of fire development and the size of the fire which are influenced by the vehicle type, conditions and cargo materials, the airflow conditions in the tunnel, the performance of the protection systems and the structural safety features of the tunnel.

The fire frequency of observed occurrences related to the traffic and accidents in a given tunnel or road should be rated by number per vehicle multiplied by kilometres to account the effect of tunnel length and traffic density [6]. Thus, from the defined characteristics of the virtual tunnel and the data available from the literature, fire rate f_r is established. The average fire rate in Italy (occurrence rate of fire = 5.6 fires per 10^9 vehicles per km) that is available from the PIARC report "Experience with significant accidents in road tunnels" [7] is used to determine the fire rate of this specific tunnel.

$$f_r = \text{occurrence rate} \times \text{AADT} \times \text{length of tunnel} \times 365 = 1.54E-02 \text{ per year.} \quad (1)$$

If risk analysis is to be done in an existing tunnel, the records of the observed accidents on that specific tunnel and other related information that is essential for the analysis can be used. Observable data analysis can be carried out assuming the Poisson hypotheses and checking them with chi-square test when the Poisson distribution model is used for the said validation.

Heat release rate (HRR), the rate of heat generation and release by fire typically measured in watts, is a very important factor in the assessment of the severity of tunnel fires [8]. So, it is necessary to associate design fires of a given HRR for each scenario to properly simulate and describe the consequences of each and consequently account the number of fatalities and the complementary number of rescued out of the present people in the tunnel. While HRR varies for different conditions, the maximum HRR that can be observed on different types of vehicles can represent design fires. From the data gathered by PIARC [9], the maximum fire power observed ranges from 2.5 MW to 30 MW for different vehicles (passenger car, van, bus and lorry with burning goods) whereas the EUREKA HGV fire test indicated a peak power output of 100 MW to 120 MW for larger vehicles (HGV) with burning goods. The characteristic of the fire can be influenced by the type of material of the vehicle itself, the type of cargo, if it carries hazardous and flammable goods, and the amount of the hazardous goods. In Italy, ANAS [4] defined the different design fires related to the different types of vehicles which are obtained from the analysis of time series of the available accident datasets.

Since the HRR is different for different types of vehicles, the traffic composition in terms of vehicle type also has an influence on the fire rate. Hence, it is necessary to include the percentage shares of the traffic (light and heavy) in obtaining the probability of fire occurrence for different fire powers.

The proportion of the vehicles were assumed to be 85% for light and 15% for heavy vehicles (Fig. 1). This was taken on the basis of EU Directive 2004/54/EC [10] saying that heavy vehicles exceeding 15% of AADT requires to assess an additional risk by increasing the traffic volume of the tunnel in calculations. For this reason, it is assumed that there is an ideal situation where the traffic share of heavy vehicles does not exceed 15%. The values mentioned are in which the limits also used as a basic safety parameter in ANAS guidelines [4] which must be checked with real data for specific tunnels. The value for heavy vehicles that should be used in the analysis must be always greater than the recorded maximum traffic share of heavy vehicles for that particular tunnel.

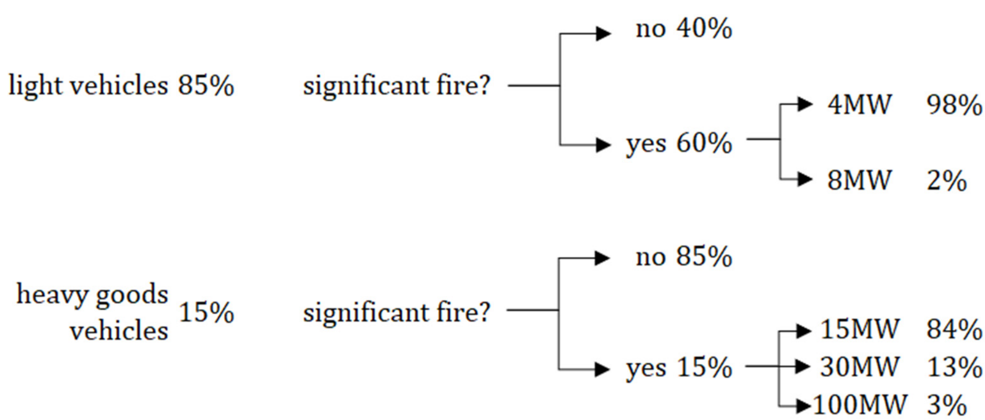

Figure 1: Distribution of heat release rate (HRR) according to ANAS guidelines.

The choice of heat release rate for fire scenarios is usually recommended by the working groups with representative members from the tunnel owners, fire brigades, regulators and consultants [9].

For this study report, the design fires are established based on the ANAS guidelines [4]. The probability of a fire accident of a given HRR, P(HRR), developed from the ANAS guidelines [4] are linearly interpolated and reclassified according to fire powers of 10 MW, 30 MW, 50 MW and 100 MW. Minor fires are the fires that do not create any injury or fatalities, or in general, the fires that are "insignificant" to risk analysis. Below you find the new probabilities of the standardized HRR fires defined (Table 1).

Table 1: Design fires and their probability of occurrence.

HRR (MW)	P(HRR)
Minor fire	7.18E-03
10	7.92E-03
30	2.52E-04
50	2.96E-06
100	7.41E-06

2.2 Temporal and seasonal characteristics of the traffic

PIARC [3] and Sandin et al. [6] both agreed that although most risk analysis used AADT, this number does not fit reality well since traffic, the number of vehicles, can vary seasonally and during the day, and therefore, this difference must be considered in the analysis.

A pattern of activities can be observed during the weekdays (Monday to Friday). Daily activities such as going to work or school are routinely made throughout the day. In Italy, working hours and school hours usually start from 8:00 or 9:00 and finish at 18:00 or 19:00.

Weekends (Saturday and Sunday) are typically spent for leisure activities like shopping and travelling with less commercial transportation. While these activities are more random compared to weekday activities, they are mostly performed within the typical working hours. It is also predicted that higher traffic will be observed in weekend than in weekday due to the reduced public transport availability.

Therefore, the observations on people's activities and the statistics from different reports became the basis for considering different days of the week and different time periods of the day in identifying the scenarios. The traffic flow during the daytime (from 6:00 to 20:00) is assumed to be higher compared to the traffic flow during the night (from 20:00 to 6:00). Consequently, the probability of an accident occurring in different periods is expected to be proportional to their traffic flow variation.

2.3 Location of the fire and people inside the tunnel

According to the PIARC report "Experience with significant accidents in road tunnels" [7], the collision rates were significantly higher in the portal area (10 m before/after tunnel portal) and in the entrance area (10–150 m inside the tunnel) compared to the interior zone (more than 150 m from both portals). When entering a tunnel, drivers experience a sudden change in illumination causing eye confusion which could trigger their driving behaviour that might result to an accident.

Although many studies reported that most of the ordinary accidents (collisions) in tunnels occurred in the entrance, only the interior zone and the exit area of the tunnel were included in the scenarios for this report. Rather than taking all the accidents (collisions) into account, the interest of this report is focused on accidents involving fire. And assuming that the vehicles downstream the accident will not be affected since they are able to exit the tunnel while the vehicles upstream might be directly exposed to the hazard since the area of accident will block the incoming vehicles, therefore for the accidents, involving fire, that will occur in the entrance area, very few vehicles will be directly exposed to the hazard and in most cases the chance of having an injury or a fatality is very low and almost zero. And despite having a high probability of accident occurring in the entrance area, since we analyse the scenarios using their quantum of risk (scenario contributions to the expected value) which is the product of the probability of the scenario and the quantified consequence in terms of fatalities, the contribution of the scenarios in the entrance area would be very low approaching to zero. Having said that, the two worst locations that seem representative for different possible locations of the fire inside the tunnel are identified as the interior zone and the exit area.

To determine the fatalities resulting from each scenario, the number of exposed units must be defined. The exposed units are not equivalent to the number of people present inside the tunnel as this will underestimate the individual risk caused by the hazard. Hence, since the vehicles downstream the accident can continue to exit the tunnel, only the vehicles queued upstream the accident are counted.

A simple queue model described by Persson [11] was used to determine the exposed units that needs to be evacuated during a fire incident. He used a time period of 2 minutes before the warning system is activated following the fire accident, and 1 minute before all vehicles notice the warning signs and stop. The vehicles used in the calculation have an average length of 3.5 m and are at least 1.5 m apart with four people inside each vehicle. The average daily traffic used is 15,000 vehicles per day, and the vehicles run at an average speed of 70 km/h.

Among the major tunnel accidents in Europe, the Monte Bianco (1999), Tauern (1999) and Gotthard (2001) tunnels, the number of persons in the tunnel reported ranges from 60 to 180 people with fatalities ranging from 11 to 39 people. Thus, for this study report, the number of exposed units is identified and limited as the minimum between the calculated "total number of people upstream the accident" and 50 (for unidirectional tunnel) or 100 (for bidirectional tunnel) (Table 2).

Table 2: Exposed units in an event of fire inside the tunnel.

Time of the day	Traffic flow (veh/h)	distance from the entrance (m)	unidirectional tunnel		bidirectional tunnel	
			total number of people inside the tunnel (upstream the accident)	**exposed units**	total number of people inside the tunnel (upstream the accident)	**exposed units**
daytime	857.14	501	198	**50**	198	**100**
		334	190	**50**	224	**100**
nighttime	300.00	501	74	**50**	74	**74**
		334	74	**50**	142	**100**

The derivation of the probabilities of the mutually exclusive initiating events are described in Fig. 2. The probability of a fire occurring with a given power in terms of heat release rate are coupled with a series of assumptions on the major key factors mentioned earlier. The factors included here are the ones that can influence the hazard scenario, independent from the impact of the safety characteristics of the tunnel such as the performance of the illumination and ventilation systems in case of fire.

HRR	P(HRR)	Probability of an accident occurring						P of the initiating event, P(i)
		days of the week		time of the day		location of the fire inside the tunnel		
minor	7.18E-03							**7.18E-03**
10MW	7.92E-03	weekday	0.60	day	0.80	mid-section	0.32	**1.22E-03**
						exit	0.68	**2.58E-03**
				night	0.20	mid-section	0.32	**3.04E-04**
						exit	0.68	**6.46E-04**
		weekend	0.40	day	0.80	mid-section	0.32	**8.11E-04**
						exit	0.68	**1.72E-03**
				night	0.20	mid-section	0.32	**2.03E-04**
						exit	0.68	**4.31E-04**
30MW	2.52E-04	weekday	0.60	day	0.80	mid-section	0.32	**3.88E-05**
						exit	0.68	**8.24E-05**
				night	0.20	mid-section	0.32	**9.69E-06**
						exit	0.68	**2.06E-05**
		weekend	0.40	day	0.80	mid-section	0.32	**2.58E-05**
						exit	0.68	**5.49E-05**
				night	0.20	mid-section	0.32	**6.46E-06**
						exit	0.68	**1.37E-05**
50MW	2.96E-06	weekday	0.60	day	0.80	mid-section	0.32	**4.55E-07**
						exit	0.68	**9.67E-07**
				night	0.20	mid-section	0.32	**1.14E-07**
						exit	0.68	**2.42E-07**
		weekend	0.40	day	0.80	mid-section	0.32	**3.03E-07**
						exit	0.68	**6.45E-07**
				night	0.20	mid-section	0.32	**7.58E-08**
						exit	0.68	**1.61E-07**
100MW	7.41E-06	weekday	0.60	day	0.80	mid-section	0.32	**1.14E-06**
						exit	0.68	**2.42E-06**
				night	0.20	mid-section	0.32	**2.84E-07**
						exit	0.68	**6.04E-07**
		weekend	0.40	day	0.80	mid-section	0.32	**7.58E-07**
						exit	0.68	**1.61E-06**
				night	0.20	mid-section	0.32	**1.90E-07**
						exit	0.68	**4.03E-07**
							ΣP(i) =	**1.54E-02**

Figure 2: Probabilities of the initiating events.

2.4 Availability of performances of the protection systems

Opacity or reduced visibility and the inhalation of toxic substances due to smoke emission influences the walking speed of the exposed units and therefore the evacuation time. According to PIARC [9], there is a linear correlation between the smoke dependent visibility measured by the optical density and the concentration of CO_2. For a given visibility of 10 m, the optical density must not exceed 0.13 m^{-1} which means that the CO_2 concentration must be around 0.05% to 0.3%. But the maximum values of 2% to 16% CO_2 were observed on different burning materials from the vehicles (e.g., seats, tyres, fuel, etc.) therefore intense smoke production might result to a very reduced visibility downstream from the fire load [9]. In addition, smoke gases in the tunnel do not only reduce the visibility but also creates health danger from possible toxicity especially from the concentration of carbon monoxide [9]. A sufficient amount of carbon monoxide inhaled by a person can cause headache, weakness, confusion, shortness of breath, and eventually can cause loss of consciousness that can lead to death with continuous exposure [11]. According to studies, the principal causes of death from a fire are due to carbon monoxide poisoning followed by carbon dioxide poisoning and oxygen deficiency [12].

Emission of toxic gases are also observed on the pavement flooring (bituminous conglomerate/asphalt) of the tunnel creating an additional impact on the severity scenario. The asphalt begins to emit toxic substances after 5 minutes of exposure to temperatures of 428°C to 530°C and catches fire after 8 minutes. The combustion of the asphalt during tunnel fire worsens the temperature and the visibility making it more difficult for the exposed units to escape. As for concrete pavement, it has an advantage in an event of fire as it does not generate heat and do not emit additional smoke, and have a better ability to maintain its characteristic in case of fire [13].

The concept of fractional effective dose (FED) can be used to determine the time until one person is incapacitated and die in the tunnel because of toxic inhalation using the two main parameters that should be considered when analysing the effects of toxic to a body – the concentration of the toxic substance and the duration of the exposure [11]. Purser and McAllister [14] said that when FED = 1, half of the population is expected to be incapacitated while and FED = 0.3 can cause incapacitation for the 11% of the population.

Based on the provisions of EU Directive 2004/54/EC [10], a tunnel with 501 m length and AADT > 2,000 vehicles per lane per day is required to have illumination and the ventilation systems. These protection systems are the two major complex protection systems that will help the exposed units to face the opacity and toxicity due to the forming smoke. And the parameters that define the performance of the protection systems concerns the technical design of the supplier and the sense of responsibility of the tunnel authorities (maintenance and recovery), and not of the risk analyser. Each initiating event is coupled with the availability of the performance of the two fundamental protection systems, giving the probability of the scenario. The "availability" described is the availability and the unavailability of the protection systems in case of an accident resulting to fire which can affect the ability of the people inside the tunnel to self-rescue.

Illumination performance and availability can be measured in terms of the total time in a year that the lighting system is able to provide illumination of a given level of lighting (lux, lumen, candela) during normal situation and a minimum level of visibility for users to allow them to leave the tunnel in their vehicles in case of electrical failure or to provide light to people walking to reach an escape route during an emergency.

As stated in the ANAS guidelines [4], emergency lighting during an electrical failure should guarantee an illumination of 1 cd/sqm for the entire tunnel for at least 30 minutes. While the safety lighting used for the evacuation of the users, in case of emergency, must illuminate the walkway with an average illuminance of 5 lux and a minimum illuminance not less than 2 lux, and with a minimum range of 90 cm.

Sandin et al. [6] performed a series of test to calculate the time it takes for a person to reach the closest unobstructed exit (100 m) and it shows that for a given unimpeded walking speed of a person with reducing visibility, the time required to evacuate increases. The unimpeded walking speed of 1m/s with visibility of 10 m, 5 m, 2 m, and 0.5 m resulted to 100 s, 100 s, 152 s, and 500 s, respectively. Moreover, the evacuation time also increases with increasing people density.

Ventilation performance and availability can be measured in terms of the total time in a year that the ventilation system is able to provide adequate air quality during normal situation and maintain a minimum level of toxicity during emergency allowing people to self-rescue.

In case of fire, the ventilation system must disperse the thermal energy generated by the fire, manage and control the smoke propagation, and exhaust the toxic and flammable substances.

Persson [11] investigates the time before the exposed people at different positions from the fire reach the critical values of FED. The scenario resulting from HGV with HRR = 20 MW shows that the people located at 10 m, 20 m, 30 m, and 40 m from the fire will not experience incapacitation before they complete the evacuation. The same findings happen for the scenario resulting from HGV with HRR = 120 MW although the critical values of FED are reached after 40 minutes. In case of pool fires, worst consequences are predicted, and shorter times are calculated to reach FED = 1.

Sandin et al. [6] also makes the same analysis using FED to determine the time to incapacitation due to the combination of carbon monoxide (CO), carbon dioxide (CO_2) and dioxide (O_2), and incapacitation due to heat. A combination of 3% CO_2, 4,000 ppm CO and 17% O_2 will reach FED = 1 at 220 s while a more disadvantageous combination with 8% CO_2, 10,000 ppm and 9% O_2 will reach FED = 1 at 35 s.

3 SCENARIO DESCRIPTION AND SIMULATION

3.1 Aims of simulations

Basically, the scenarios simulations aim to numerically calculate the number of estimated fatalities coupled with any design scenario. Each one of the above scenarios is also coupled with the estimation of its probability of occurrence estimated with the parallel established procedure based on the tree diagram.

Each design scenario does correspond to one specific branch of the tree diagram. Each simulation provides our estimated value of the number of fatalities that can be compared with the number of people present in the considered tunnel and out of them with the number of the ones that are inside the distance of influence (potential damages) from the fire accident location.

The last number mentioned above is the estimation of the so-called exposed units number. The ratio between the number of fatalities and the exposed units is a first rough estimate of the mortality rate of the given scenario.

The quantum of risk estimate need the corresponding value of the estimated probability of the scenario itself. The simulations include the protective effect of the mandatory protection systems active in a tunnel according to length, volume and composition of the traffic.

The simulator does create exactly the geometrical and exposure conditions of the specific tunnel in which will take place the initiating event of fire accident and consequent processes of toxicity diffusion and exposed units evacuations (Fig. 3).

3.2 Necessary INPUTS and expected OUTPUTS

Location coordinates and initial walking speeds of the exposure units participating to a given scenario have to be available. The geometrical, architectural and structural condition of the Tunnel have also to be available.

The heat release rate curve and the performance levels of the available protection systems have to be specified.

The number of fatalities for each given scenario are then expected together with the details of the available safe egress time (ASET) and the required safe egress time (RSET) for each one exposure unit.

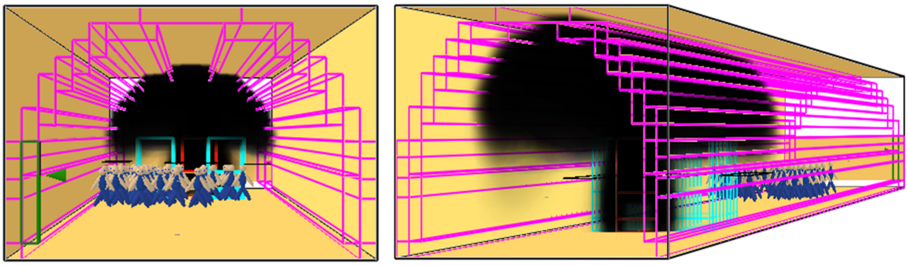

Figure 3: Two views of the exposed units locations, each of them walking with an assumed walking speed at the same moment in time. All the data are recorded and available for processing purposes from the fire initiating event time to the final picture accounting for number of fatalities and rescued people (exposed units). The above data are relevant for the aim of optimizing the risk-based design model.

4 SCENARIO PROBABILIZATION AND RISK QUANTA GU@LARP MODEL

In total, 128 representative scenarios are identified from the combination of the different conditions and factors that are most relevant to the risk analysis of this tunnel. Now, the methodology used for scenario probabilization is described on the following paragraphs.

The scenario tree diagrams of the initiating events are the computational tools allowing us to measure the quantum of risk of each simple scenario by considering the impact of the performance of the protective systems, the illumination and ventilation systems, on the hazard flow in terms of the lack of visibility and the lack of breathability (Fig. 4).

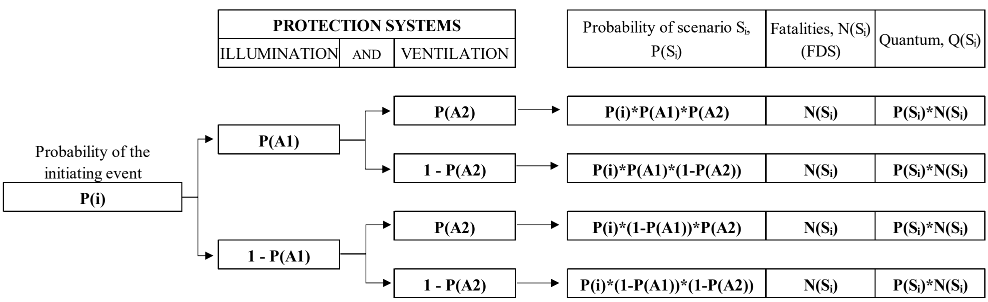

Figure 4: Scenario tree diagram of an initiating event.

Each tree produces a complete group of mutually exclusive scenarios originating from the same initiating event and therefore share the probability of the initiating event among them. The probability of each scenario $P(S_i)$ being given by the corresponding simple tree branch is the product of the probability of the initiating event P(i) and the complex of the performance of the illumination and ventilation systems. The quantum $Q(S_i)$ is then the result of the probability of scenario multiplied by the corresponding number of fatalities $N(S_i)$ given by the fire dynamic simulator (FDS).

Finally, for the risk-based design, the quantum of risk of each scenario can be compared and ranked according to its severity – the higher the quantum, the higher the risk. Table 3 shows the calculations for the unidirectional virtual tunnel.

Table 3: Ranked quantum of risk.

	Scenario, S_i*		Probability of the Scenario, $P(S_i)$	Fatalities, N_i	Quantum, Q_i
1	5	10, WD, D, E, GI, GV	1.74E-03	5	8.72E-03
2	6	10, WD, D, E, GI, PV	5.81E-04	15	8.72E-03
3	1	10, WD, D, M, GI, GV	8.21E-04	6	4.92E-03
4	21	10, WE, D, E, GI, GV	1.16E-03	3	3.49E-03
5	21	10, WE, D, E, GI, GV	1.16E-03	3	3.49E-03
6	2	10, WD, D, M, GI, PV	2.74E-04	11	3.01E-03
7	7	10, WD, D, E, PI, GV	1.94E-04	12	2.33E-03
8	17	10, WE, D, M, GI, GV	5.47E-04	4	2.19E-03
9	13	10, WD, N, E, GI, GV	4.36E-04	4	1.74E-03
10	14	10, WD, N, E, GI, PV	1.45E-04	12	1.74E-03
11	8	10, WD, D, E, PI, PV	6.46E-05	20	1.29E-03
12	18	10, WE, D, M, GI, PV	1.82E-04	7	1.28E-03
13	9	10, WD, N, M, GI, GV	2.05E-04	5	1.03E-03
14	23	10, WE, D, E, PI, GV	1.29E-04	7	9.04E-04
15	3	10, WD, D, M, PI, GV	9.12E-05	8	7.30E-04

Among the 128 scenarios identified, the 15 scenarios with highest quantum of risk are shown on table comprising the 86% of the total quantum of risk of the tunnel analyzed. It is evident that the *scenario 5* with HRR = 10 MW occurring during the weekday (daytime) at the exit zone of the tunnel with good illumination and good ventilation gives the highest contribution to the total risk followed. Despite having a good performance of both the illumination and ventilation system that, the scenario 5 gives the quantum of risk due to its high probability of occurrence.

In the risk-based design, these information regarding the possible scenarios in case of fire is important to determine the compliance with the risk acceptability/tolerability criteria, following the ALARP principle or "As Low as Reasonably Practicable", to check if the minimum level of safety is guaranteed in the tunnel. When the risk is intolerable, risk reduction must be made regardless of the cost; when the risk is tolerable, it is necessary to check if risk reduction is not further possible due to unbalanced cost vs benefits; when the risk is acceptable, no additional measure is required.

Fig. 5 presents the graphical representation of the societal risk (frequency–number of fatalities curve) of the tunnel evaluated based on the criteria established by the Italian Legislative Decree 264 [15]. The acceptable risk corresponding to the abscissa fatality N = 1 is 10^{-4} per year and the abscissa fatality N = 100 is 10^{-6} per year. Whereas the tolerable risk corresponding to N = 1 is 10^{-1} per year and N = 100 is 10^{-3} per year.

The "tolerability risk line" and "acceptability risk line" correspond to the exceedance probability distribution function according to the Gu@larp model. The Gu@larp density function is $g(N) = Gu/N^2$ and the corresponding exceedance probability is $G(N) = Gu/N$ where Gu is the risk indicator which is the value of the ordinate at N = 1.

The "risk line" shows the exceedance probability curve of the societal risk in the tunnel. For a given number of fatalities N in the abscissa, the probability of exceedance is equal to the result of back-cumulation procedure of all the probabilities of the scenarios with higher than or equal to that threshold N. The area below each staircase of the exceedance probability curve is then the summation of the quantum E of all scenarios having the same number of fatalities N.

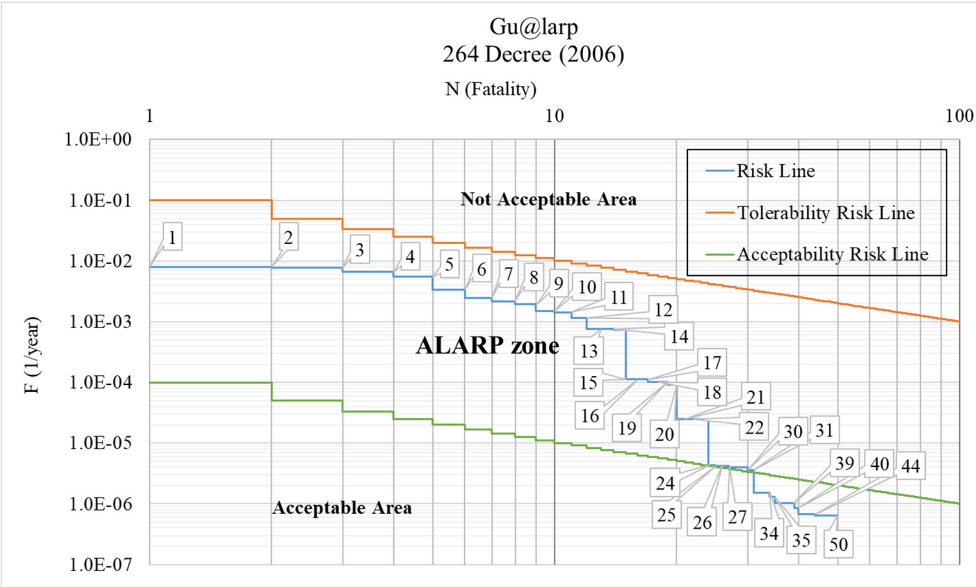

Figure 5: ALARP criteria based on the Italian Decree 264.

The question of risk-based design is whether to improve the scenario with the highest risk or the scenario with the highest fatalities. In reality, people would be more concerned about the scenarios with the highest fatalities more than the scenarios with low fatalities. More often, the probability of scenarios with high fatalities are extremely low which also results to low quantum of risk. And since higher quanta indicates greater space for improvement and therefore, improving “high-risk” scenarios might largely contribute to the reduction of societal risk rather than improving “high-fatalities” scenarios.

5 CONCLUSIONS

The Gu@larp risk quantum model is fully respectful of the concept of risk quantitative measure for forensic and societal purposes as has been for the first time but very clearly stated in the 1969 UK court judgment by the judge Lord Asquith.

The individual risk indicator is firstly clearly stated in relationship with the concept of quantum of risk of a given scenario out of a well identified specific corresponding design scenarios.

From the quantum of risk coupled with the all necessary design scenario the requested risk indicators for the compliance with the acceptability and tolerability risk criteria are immediately calculated.

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