Italian Risk Analysis Method

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SUMMARY: the development of risk analysis in tunnel safety design has supplied an innovative answer to the methods required for a substantial improvement of tunnels safety, a need that was strongly felt by public opinion after the serious accidents over the last few years (Mont Blanc, Gottardo). The new laws,both at European and national levels, have replied to this recent demand and have made their own the new project groundwork enabling to quantify risks; therefore, were created the fundamental principles to start a large intervention program of safety implementation for road, railway and metropolitan tunnels. These measures will contribute to place Italy at the avant-garde in tunnelling, world-wide, once more. This paper will show IRAM that concerns the accidental events considered as critical in the specific and costricted road and railway tunnel environment, in other words: fire, collisions, derailing, flammable material and toxic and hazardous substances discharge..

1 DESIGN CRITERIA FOR TUNNEL SAFETY

The development of risk analysis in tunnel safety design has supplied an innovative answer to the methods required for a substantial improvement of tunnels safety, a need that was strongly felt by public opinion after the serious accidents over the last few years (Mont Blanc, Gottardo).

The new laws, both at European and national levels, have replied to this recent demand and have made their own the new project groundwork enabling to quantify risks; therefore, were created the fundamental principles to start a large intervention program of safety implementation for road, railway and metropolitan tunnels. These measures will contribute to place our Country – by itself its has 60% of European tunnels – at the avant-garde in tunnelling, world-wide, once more (fig 1).

The necessity to use quantifying assessment criteria and to adopt a systematic approach method, stems from the fact that hazard perception - in other words the psychic perception of danger - is subjective because it is related to the degree of familiarity that a subject has with the system employed (equipment, plant, structure, etc.).

Therefore, it is not possible to resort to a simplistic listing of provisions to implement for the infrastructure safety, unless the most likely hazards and admitted safety standards have been defined beforehand.

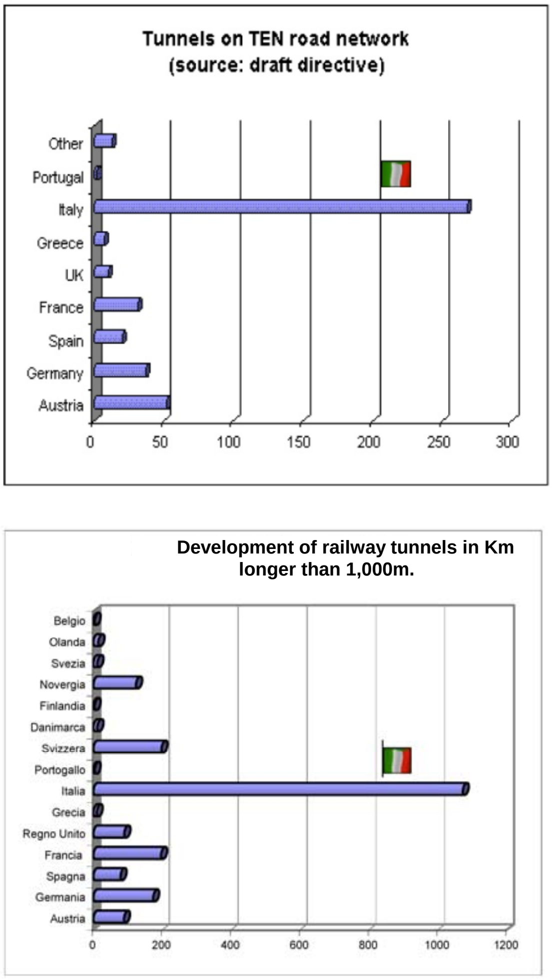

Figure 1 Development of road and railway tunnels in Europe

Such method offers the advantage to avoid that tragic events, involving the emotional sphere, induce to disproportionate safety interventions, with added financial costs of a scale hampering a country’s investing potential and subtracting resources that could be devoted to top priority works. On the contrary, a correct and coherent approach to the genuine requirements of a given infrastructure allows to optimize investments, and this makes the achievement of large-scale safety objectives more realistic.A further advantage achieved when adopting targeted interventions to a specific tunnel system is that this avoids implementing earlier standard solutions, evenly applied to all cases, while concurrently promoting the research for innovative technological solutions.

In particular, the 2004/54/CE Directive identifies the target safety objectives, a system of safety parameters to enforce, it fixes the sets of minimum safety requirements to satisfy and it defines the risk analysis as the instrument to employ for the assessment of a tunnel’s safety standards.It is important to define risk as the realistic occurrence deriving from a potential hazard.

Safety means the complex of conditioning actions that population’s behaviour, the structural solutions, the technological systems and control and management procedures apply to risk.The two concepts are interrelated according to the formula as follows:

Risk = Hazard x (Safety) - 1

The above formula allows to comprehend that nil risk is impossible to attain.

Risk is not a physical parameter, therefore not quantifiable; however, it is possible to mathematically define risk using the group theory. According to this theory, risk is defined as an application (ref to Ill. 2) of the group of hazardous events and the consequences group. Both of these groups are probabilistic. The consequences group defines the potential damage that can be related to a system of possibly hazardous events.

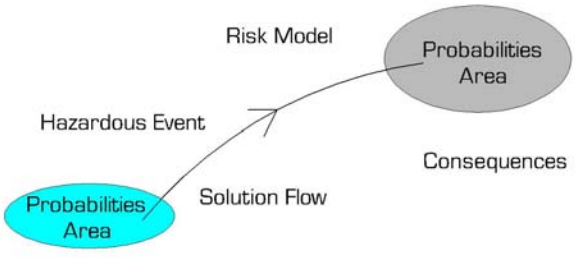

Figure 2 Risk as an application among/between probability groups

The methodological principles, as indicated by the Directive to the effect of achieving the safety objectives, have been taken as the basis of the tunnel safety design method developed in Italy; moreover, the Directive has represented a highly significant, legislative document to implement a consistent attitude within the European Union, translating into a consistency of technical solutions and of the safety standards adopted.

Notwithstanding the necessity of adapting it to every individual tunnel specifications, such design method combines the principles and techniques of performance design, of the consequences analysis and the probability approach with the risk analysis as adopted by various European Union States when assessing the risks of the transit plants.

It also represents the technical basis of the new legislation in road tunnel safety (n° 264 Legislative Decree dated 05.10.2006 in function of the 54/2004/CE Directive), and in railway tunnels safety (Interdepartmental D. dated 28/10/2005: “Safety in Railway Tunnels”).

The scientific-technical, in-depth research carried out over the last few years in the engineering safety field has enabled to identify the logical sequence of reference for a tunnel safety project and the analytical methods to apply.

The procedure of safety design for road and railway tunnels is according to the phases as explained in detail in figure 3.

1.1 *Acquisition of geometrical, structural and plant characteristics data related to the works and to accident probability; setting of data-bank according to coded criteria*

Similarly to all design project, safety design can’t overlook the compilation of a database as follows:

- the works’ geometric characteristics, with specific reference to length, cross section shape (number, lanes width and direction, height or overall dimension, footpath, etc.); the road layout geometric characteristics and – for existing works – typology and year of construction. For projects at design stage these parameters represent the initial hypothesis, and are subject to modifications deriving from the safety check of the works.

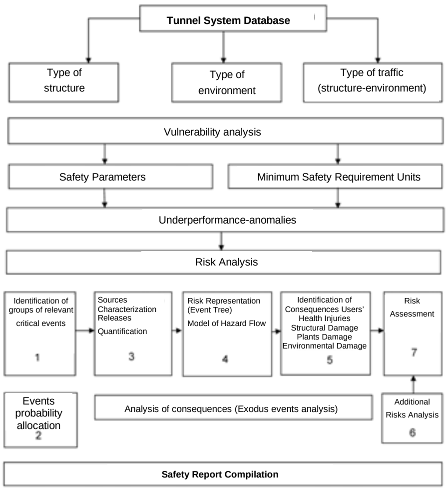

Figure 3Flow diagram for tunnels safety design

- The environmental characteristics of the surrounding context concern the weather/climate conditions, mainly at the tunnel entry-exit, the tunnel accessibility and the possibility of localizing rescue teams.

- The traffic characteristics in terms of volume and type of traffic, traffic regimen (high-speed curves) and expected standard of service.

1.2 *Analysis of structural vulnerability*

Upon completion of the database follows the elaboration initial phase consisting in assessing the tunnel system vulnerability, identifying the potential hazards related to the tunnel system and the possible hazardous scenarios.

The Vulnerability Analysis allows the identification of possible safety parameters inconsistencies as well as underperformance related to the minimum, legally-set requirements; it enables to identify the risk analysis procedure to apply in the subsequent phase and to achieve an outline of the type of risk of the tunnel system, to subsequently proceed with the individuation of the most appropriate design solution.

1.3 *Individuation and design of the safety requirements in structural and plant engineering terms*

From the vulnerability analysis, the safety designer can comprehend which safety instruments must be selected among the preventative, protection or mitigating measures (escape-facilitating), the geometric and structural measures and the plant measures that current norms define as a minimum - either compulsory of optional - in certain conditions.

In particular, the Transports and Infrastructures Ministerial Decree, in cooperation with the Internal Affairs Ministry, dated 28th October, 2005 (G.U. n. 83 dated 8th, April, 2006) defines the safety requirements (minimum and integrative requirements) to adopt for the safety of more than 2000 railway tunnels existing in our Country and for those under construction and at design stage.

Such norms refer respectively to the sub-groups: Infrastructure, road and rail network materials and Operation Procedures. Within this context, the rules directives recommend to minimize the infrastructure interventions – traditionally expensive and with high running costs – to the benefit of plant systems and new technologies such as, for example, fire extinguishing systems able to contrast the onset of fire.

Likewise, the n. 264 Legislative Decree dated 5th, October, 2006, in function of the 54/2004/CE Directive, identifies the minimum requirements for new and existing tunnels, listing them as structural and plant requirements. The safety design and the risk analysis must individuate alternative solutions that guarantee a safety standard equal or higher in case such requirements are impracticable or only possible at disproportionate cost.

Therefore, safety design for both road and railway tunnels, entails the identification of structural solutions, plants equipment, managerial provisions - including innovative ones enabling the achievement of safety targets – and the subsequent check of the solutions selected using a quantifying risk analysis.

1.4 *Risk analysis to check the achievement of safety targets*

From this stage, the design process proceeds with the study – including the probabilities viewpoint – of hazardous events starting from the causes possibly generating events at the origin of a process that transforms a potential hazard into a real risk, to the individuation and categorization – in terms of probabilities of occurrence and damage - of the end-of-emergency scenario.

The representation of possible accident causes and the identification of occurrence probabilities of the original critical events are illustrated by the causal tree technique (FMA – Failure Modelling Analysis). The causal tree also allows to represent the action as supplied by the preventative measures for originating events that can develop into incidental scenarios.

The group of accidents scenarios related to the tunnel system is defined using the events tree technique, whereby each branch represents a possible incidental scenario. The actions aiming at conditioning the development of an accident scenario are supplied by the protection and mitigation safety measures.

The quantitative risk analysis used in the safety design process can be clearly illustrated by the so-called “butterfly” diagram.

The diagram structure (fig. 4) shows two different sections individuating the field of application of the FMA (Failure Modelling Analysis) technique and of the ETA (Event Tree Analysis) technique as separate from the Original Critical Event.

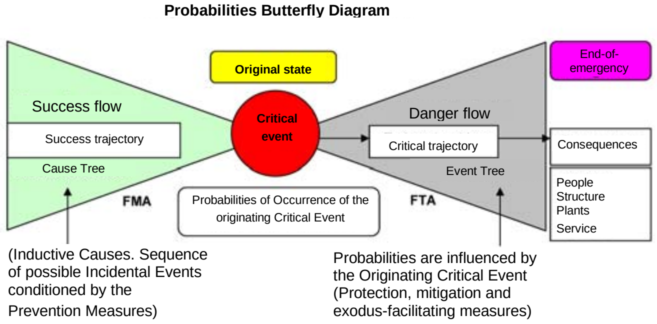

Figure 4Butterfly diagram

The butterfly diagram right hand sector concerns the group of the trajectories of the system’s probable accidents, the causes potentially inducing the system development on different accidents trajectories, the conditioning action that the protection and mitigation measures apply on the achievement of the end-of-emergency situations.

The critical accident scenarios for the tunnel systems relate to events characterized by a low-occurrence probability and high consequences satisfying the utmost statistics, i.e. with low probability of occurring and significant consequences.

In particular, the iterate application of the risk assessment model - as defined by the Legislative Decree n. 264 dated 05/10/2006 (concerning the enforcement of the 2004/54/CE Directive in the matter of trans-European roads network safety) - to the range of Italian roads tunnel systems, allows the formulation of a simplified risk procedure analysis (risk calculator). Such procedure defines the risk level of a safety project using one single, focused operation between distribution functions representing the occurrence ratio of hazardous events and the expected consequences on the sensitive elements of the tunnel system, supported by the comparison of results supplied by models with the trend lines derived from the statistical analysis of real data.

For what concerns the analysis of consequences deriving from an accident, the literature identifies two different methods. One is the risk analysis using a criticality matrix, compiled via the introduction of occurrence probability of hazardous events, assessed on the basis of a statistical analysis of tunnel accidents and adopting the experts' assessment to fix the expected consequences on the tunnel system's sensitive elements. This method individuates the classes of risk expressed as a uniform probability distribution.

The other method is represented by the risk analysis using the event tree: this supplies a deterministic analysis of the consequences and it's carried out assuming the existence of a dimensioning event and assigning an ideal reliability and efficiency rating to safety barriers. The outcome is the identification of risk levels expressed as distribution of continuous probabilities (complementary collective curves).

The Legislative Decree adopts this latter method (event tree) whereas the one defined by the criticality matrix, a somehow empirical and approximate formula in determining the risk level related to a safety project, is not considered by the Decree.

1.5 *Emergency plans in compliance with recently issued norms*

The safety project defines the preventative measures and the protection systems and devices necessary to guarantee users' and rescue service personnel's safety, and for road and railway tunnels, it will be inclusive of safety management documents for the tunnel's first opening procedures and for periodic tasks.

In particular, the safety design will be inclusive of:

- preset management procedures to guarantee the tunnel working order and maintenance;
- an emergency-management plan in cooperation with first aid services and responsive to users' and rescue specialized personnel requirements;
- an acquisition and updating system of significant events, accidents and malfunctions and their analysis;
- the safety tests plan as carried out;
- the personnel training program.

For what concerns the safety project of new tunnels, the design must precede all other geo-technical, structural and plant project as this preparatory design phase will generate the reference lay-outs for the works characteristics. Such features have often consisted in preset solutions, based more on conventional practice than on an attentive design able to guarantee the genuine safety of the works and maximizing the Country's financial resources.

2 RISK ANALYSIS

2.1 *The IRAM method (Italian Risk Analysis Method)*

The risk analysis method, whose application methods are hereunder detailed, concerns the accidental events considered as critical in the specific and constricted road and railway tunnel environment, in other words: fire, collisions with fire, derailing, flammable material and toxic and hazardous substances discharge.

For what concerns events connected to road accidents as such, related to the infrastructure's geometric characteristics, not induced by the tunnel specific environment and not involving additional risks to those related to road traffic, in order to ensure prevention, they are to be considered and tackled within the road traffic rules and road design.

The victims of this latter type of accidents are to be computed as road casualties.

The Risk Analysis carried out according to the classic Bayes' method, using the uncertainty analysis, is the correct analytical method identified acknowledged as appropriate to define the risk level specific to the existing road and railway Italian tunnels, as according to the recommendations by the 2004/54/CE Directive and Ministerial Decree 28/10/05.

Thanks to the systemic approach employed, it is possible to define the users' survival rate in possible escape scenarios considered as critical and consequent to accidents, within the tunnel specific environment, and to quantify the risk related to the individual tunnel over a set time-frame.

As previously illustrated, the safety design procedure for road, railway and metropolitan tunnels entails a previous analysis of the infrastructure vulnerability that establishes a univocal relation between homogeneous groups of minimum safety requirements as set by the norms, and the limit safety parameters as defined by the statistical analysis in historical data of accidents.

The vulnerability analysis allows to identify anomalies of safety parameters and shortfalls of minimum parameters as set by the norms, and to identify the structures requiring to undergo risk analysis.

For what concerns road tunnels, the risk analysis must be carried out for every tunnel that does not comply with minimum parameters and thus requires the adoption of alternative safety measures in order to demonstrate that they can guarantee an equivalent or higher safety level; in other words, every tunnel having unusual characteristics as compared to the parameters set by the law.

1,000 to 9,000 metres long railway tunnels non complying with minimum requirements, tunnels longer than 9,000 metres and tunnels where the simultaneous presence of commercial trains or trains transporting hazardous substance is possible, or in presence of specific risks close to the tunnel entry-exit, must undergo an in-depth risk analysis to identify specific provisions to be applied on a case-by-case basis.

The safety minimum requirements are mainly set to specifically provide for:

- tunnel system's protection and mitigation for overall hazards deriving form critical events, such as reduction of safety systems' intervention time, reduction of fire hotbed temperature, control of fumes dispersion;
- facilitation of self-rescue escape operations such as emergency exits, improved visibility and communication means;
- facilitation of emergency rescue operations such as road accesses, improved communication means and water supply.

Some of the above mentioned requirements also hold a preventative role during standard working conditions.

The risk analysis must demonstrate that the overall preventative, protection, mitigation measures for the tunnel's overall hazardous situation deriving from critical events and the exodus and rescue facilitation can ensure that the structure risk level remains below the satisfactory risk level and cannot be further improved other than with unrealistic works or at a disproportionate cost (cost-safety analysis).

The major points of the risk analysis are summarized in the conceptual diagram in figure 5

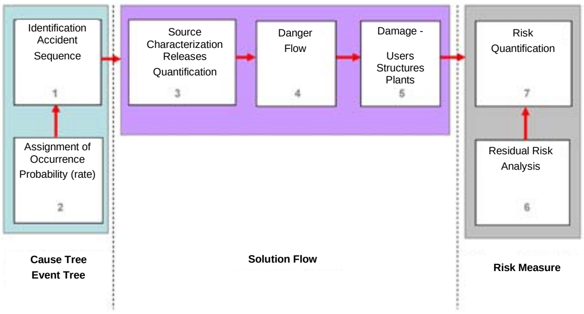

Figure 5 Risk analysis flow diagram

2.2 *The cause and event tree*

The accidents scenarios are illustrated by models inclusive of the cause tree, the critical event, the event tree.

The critical event is defined in terms of occurrence probability and potential hazard on the basis of statistical evidence for tunnel systems as a whole, possibly integrated by data available for the individual tunnel under consideration, with reference to occurrence rate detected and the tunnel design specifications.

The event tree is defined in terms of occurrence probability of critical events and of probability of development along specific branches, as conditioned by the safety systems action quantified in terms of their reliability and efficiency.

The event tree branches finish off in end-of-emergency scenarios, defined by the number of permutations mutually excluding the conditioning actions implemented by the mitigating procedures provided for.

Figure 6 shows and example of application of the event tree technique to define fire-prevention safety in a tunnel assumed to be equipped with safety systems as follows:

- Monitoring-detection,
- Communications,
- Ventilation,
- Illumination.

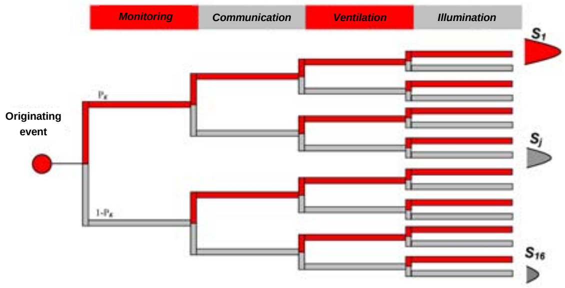

Figure 6 Event tree

2.3 *The coding of risk sources and scenarios*

In order to ensure a universal basis of input data for the application of the risk evaluation assessment method to the experts involved in the safety plan program, it seems necessary to code the sources and hazard scenarios.

The fire scenarios in tunnels are defined on the basis of the chemical-physical parameter of the fire sources thermal power. The parameter used for thermal power generated by a fully developed fire is estimated starting from the energy of the type of fuel feeding the fire and using a semi-empirical formula derived from experimental data attained during tests carried out in real-life situations, with natural ventilation, within the Eureka Project and the Memorial Tunnel experimental program.

The thermal energy released rate during the event is defined by modelling the development phase, the still phase and the extinguishing phase, using analytical functions appropriate to reproduce the thermal energy release path as shown in the graphs of the test's details and reported by public domain literature.

The effect of tunnel ventilation on the fire-generated thermal power development is taken into account introducing an appropriate ventilation factor as defined by the application of the Bayes' analysis to the experimental data detected during real-life tests or in laboratory tests and reported by public domain literature.

The combustion phenomenon is defined by a simplified model, introducing the relevant parameters as in the subsequent characterization of the micro-climate occurring in a tunnel during a fire (oxygen consumption, carbon dioxide and carbon monoxide production, smoke curtain), that are appropriate parameters in function of the fire-generated power.

The description of the combustion phenomenon using advanced model is admitted as far as they produce an outcome that can be comparable or improved as compared to the simplified approach results.

The statistical definition of fire scenarios in terms of occurrence probability and intensity of fire, as defined by the historical tunnel-accident series analysis attained from public domain literature, is carried out using the event tree technique.

The data variation about thermal power released from fire hot-beds of different nature, inclusive of those with a highly flammable potential, is taken into account introducing specific distribution functions. The proposed coding of hazard sources and scenarios can be adjusted, providing it is documented with detailed references to scientific publications related to approved innovations concerning occurrence modalities and events of fire development in tunnels. A similar coding is adopted for hazardous goods sources and related hazardous scenarios.

2.4 *Risk-flow modelling*

The risk flow is outlined as a sequence of situations defined by the evolution of chemical and physical phenomena consequent to the occurrence of an hazardous event, whose development is conditioned by the safety barriers restraints (emergency trajectories of the tunnel system).

The risk flow is defined applying the thermo-fluid-dynamic method, quantifiable at differently detailed levels, and represented using the event tree technique.

Among the models employed to quantify the risk flow (concentrated parameter models, zoning models, network models, field models) the most widely adopted are the field models.

The value of a risk flow simulation is defined by the models reliability and by the accuracy of solutions.

The outcome of risk flow simulation, carried out employing the models adopted with statistical techniques – in order to include the consequences of epistemic uncertainties related to the safety barriers' performance and the description of hazardous phenomena – defines the paths of space and time variables characterizing the hazardous phenomena (temperature fields, toxic and hazardous substances concentration fields).

Figure7 shows an example of risk flow simulation inside a tunnel, as carried out designing a field model for a fire generated by a hot-bed generated by a heavy-duty vehicle, and in natural ventilation conditions; this was solved using the Fire Dynamics Simulator free-fire code.

The risk flow defines the hostile environment that construction materials, the structure's cladding and the emergency management systems are exposed to, within which users implement the escape course of action and rescue teams put into operation the intervention procedures. The fields of variables characterizing the risk flow are used to define, using appropriate statistical models, the consequences on the tunnel system sensitive elements (damage vector).

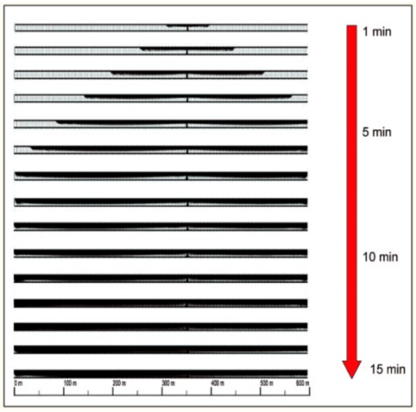

Figure 7 Risk flow simulation inside a tunnel

2.5 *Characterization of tunnel traffic and escape simulated scenarios*

In case of accident, the time required to close the tunnel must be compared with the time required by the vehicles queue's travelling time. Illustration 8 shows a possible diagram of queue formation process.

The users' escape from a tunnel is a course of actions carried out by groups of individuals with specific behaviours, moving along a rough terrain and in an hostile environment.

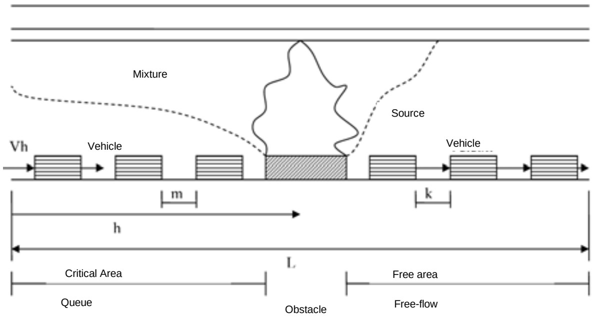

Figure 8 Queue formation in a tunnel

The elements used to define a simplified simulation method for escape scenarios are:

- Geometric parameters appropriate to define emergency exits and obstacles on the exodus path, the users' spatial distribution in the event initial stage;
- Distribution functions appropriate to define the time phases within which the exodus procedure unfolds (perception time, reaction/response time, evacuation time):
- Chemical-physical parameters appropriate to define the hostile environment within which the escape procedure takes place (the field of variables representing the risk flow).

The exodus process simulation can be designed developing models of formal complexity, increasing in function of the size of the escape path taken as representative, of the approach used in the formulation, of the adopted solution techniques. Among the models that can be employed (mono-dimensional, bi-dimensional, Lagrange or Euler models, deterministic or statistic techniques) the one apparently offering the best outcome is the Lagrange method, that allows to define the movements of each person involved in the event, and that can include the interaction among individuals, using appropriate interaction prospectives.

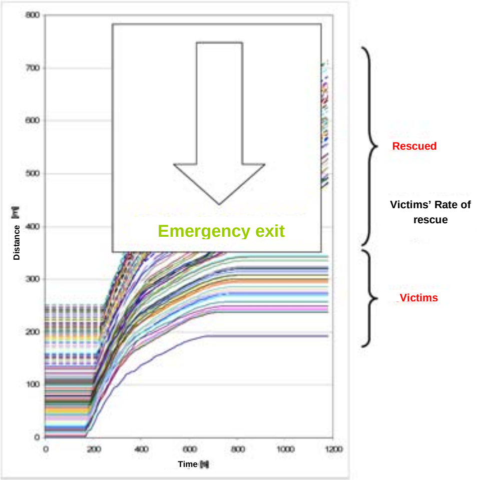

Figure 9 Escape scenario simulation

The Montecarlo method generates a statistically significant sample of persons involved in an escape.

The curves in the illustration 9 graph represent the distance of a person in function of the time: in the simulation, the victims are represented by the curves tending to become asymptotically horizontal, evidence of the end-of-escape due to environmental conditions incompatible with survival.

2.6 *The risk magnitude*

According to the consequences, the risk extent can be classed in:

Variable	Measure
Victims' number (N)	Individual Risk Social Risk
Financial damage (DE)	Direct Costs Indirect Costs

The variable taken as representative when defining risk magnitude is the number of victims consequent to a critical accident event.

The risk magnitude adopted by current law is the Social Risk magnitude.

The social risk extent as suggested by the literature is susceptible of graphic representation or in terms of analytical formulae.

Social risk is normally calculated assessing the event frequency over a "f" year and the "N" number of victims related to each individual event identified and possible consequences.

Each "f-N" combination can be represented by a dot on a graph, thus generating histograms knows as "f-N-curves".

The area between the Reasonable Risk curve and the Acceptable Risk curve defines the area of application for the "ALARP" (As Low As Reasonably Practicable) principle; such principle, taken as the guiding criteria for the costs-safety analysis, establishes that the lessening of risk level in a specific tunnel must be compatible with the structural project's intrinsic, technical and financial restrictions. The optimal design solution originates from the combination – accurately carried out on strict bases - of the preventative and protection safety measures deemed appropriate to ensure an acceptable risk level for the tunnel under consideration.

The sphere of the compensating measures is the area of the ALARP principle, in accordance with the risk analysis methodology adopted by law.

The risk level intrinsic to a generic tunnel is defined by the cumulated complementary curve (C.C.C.).

The cumulated complementary curve – inclusive of all available information concerning occurrence frequency of a group of significant accident events and the related consequence probability – allows to represent the risk as a complete distribution of potential loss, highlighting the uncertainty effect related to malfunction or to the inadequacy of the safety systems adopted.

The area subtended by a cumulated complementary curve originates a global risk indicator appropriate to define the conditions of equivalence among various design solutions for a tunnel system, as it defines beforehand the appropriate comparison criteria that take into account the uncertainties related to the system.

As a Cumulated Complementary Curve can be related to a cumulated distribution function, it cannot be defined in terms of a single moment (expected damage value).

The line representing the Reasonable Risk is compatible with the tangential enveloping perpendicular to the complementary cumulated curves related to the actual tunnels if complying with all minimum safety requirements and reliable and efficient safety systems according to current good practice recommendations.

2.6.1 *Road tunnels*

In case of road tunnel, the curves F-N (fig. 10) represent - on a logarithmic scale - the function:

$$1-F_N(x)=P(N>x)=\int_x^\infty f_N(x)dx$$

where $F_N(x)$ is the probabilities distribution function of victims' number per year, $f_N(x)$ is the probabilities density function of victims' number per year.

The social risk criteria related to a road tunnel is as follows:

the risk of accident event - a single event causing 50 or more deaths - must be considered as inadmissible if the frequency has been assessed as higher than 1/500 per year (F = 2·10-3 per year; N = 50).

The line through the coordinated point F-N as indicated, with a slant equal to “-1”, defines the Admissible Risk level.

The line attained translating in a rigid mode 3 decades below the line representing the Maximum Admissible Risk, defines the Acceptable Risk Level.

This line corresponds to “fatality 1” (N=1) over 1/10000 per year (F = 10 -4 per year); similarly, “fatalities 100” (N= 100) correspond to 1/100000000 per year (F = 10-6 per year).

The risk level coinciding to the line on the F-N plane passing through the point (1, 10-2) and slant equal to -1, is compatible with the perpendicular enveloping tangent of the complementary cumulated curves in tunnels equipped with the safety measures in compliance with ANAS standards.

The ANAS standards define a safety level higher than the admissible limit and it is compatible with the tunnel safety, performance design.

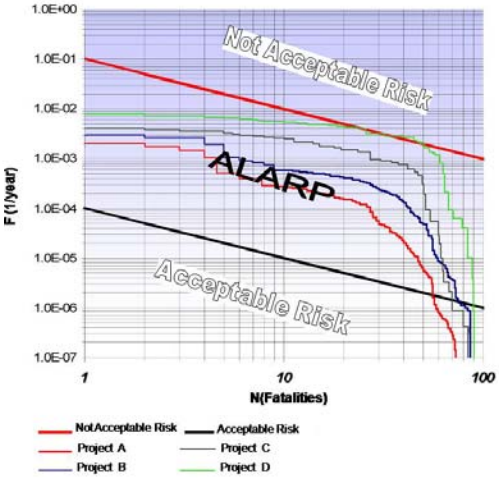

Figure 10 The F-N diagram related to road tunnel safety

2.6.2 Railway tunnels

The quantitative risk analysis in railway tunnels must be set within an overall framework of system logics, adapting it to the specific train-tunnel system and articulated in the sub-groups of either structural or functional nature, according to what prescribed by the 96/48CE Directive dated 23/7/96 and 2001/16/CE dated 19/3/2001 and subsequent deliberations.

More in detail, the risk analysis must refer to the division of the train-tunnel system into the sub-systems forming the infrastructure, road and railway network materials and operational procedures.

Some accidents, reference scenarios related to emergency in tunnels, have been identified as derived from the onset of critical events:

- fire;
- derailing;
- collision.

The three reference scenario of accidents can develop towards static, differential end-of-emergency configurations characterized by different levels of injure to humans, and damage to materials and infrastructures, according to the correct working order or malfunctioning of protective and mitigating protection measures enforced at the levels as follows:

- infrastructure sub-system;
- road and railway network materials sub-system;
- operational procedures sub-system.

Due to the uncertainty in measuring the damage, the admissible risk must be assessed beforehand valuing the single element contributing to passengers’ safety.

The results of the Events Tree analysis supply the evaluation of occurrence probabilities distribution of the damage level related to the consequences of the accidents reference scenarios.

On the basis of such data, is estimated the Overall Expected Risk (R) for a specific work and a specific traffic regimen.

This can be expressed as:

$R= \sum_{i=1} p_i C_i$

where:

R= expected risk;

pi= occurrence probability of the infinitesimal consequence;

Ci= value of the damage indicator related to the infinitesimal consequence;

n= number of consequential events.

The individual Expected Risk (IR) is attained normalizing the previous indicator value to the population exposed, within a preset time-frame (one year) per tunnel-travelled kilometre.

Moreover, the Cumulated Risk (CR) is also clearly defined on the basis of cumulated probabilities distribution of the damage level, still referred to one year time.

The cumulated risk level supplies the (cumulated) probability of a greater damage for a given admissible threshold.

The individual expected risk, along with the cumulated risk, forms the reference parameter for the acceptability of a passenger’s safety level related to a single, specific tunnel.

According to literature data, for freely taken risk, statistic data record an individual, per-year risk between 10-4 and 10-5, whereas for the involuntary risks it is between 10-6 and 10-8.

According to the conservative hypothesis that each user travels an average of 1,000 km per year on the railway system, the individual risk in tunnel is set at 10-9 fatality/(passenger-km per year).

According to what above described, the individual risk defines the expected yearly risk per passenger per kilometre; the alert threshold is set at 10-11 and the inadmissible threshold is at 10-9.

If the calculated risk falls within the alert area, it is required to exhaustively document the precision and validity of the data employed as well as the accuracy of the procedure; in case of residual uncertainty, it is required to proceed with a type-ALARP assessment.

The cumulated risk indicator allows to assess the effects of dangerous events evolution on exposed passengers.

As admissible criteria for the cumulated risk, proceed with an analysis of a criteria defined as occurrence probability – over a set time frame (e.g. one year), per tunnel kilometre (N/km/year) – of a preset number of fatalities.

In order to identify an admissible threshold, it is introduced a limiting criteria on the P plane ([N/Km-year]>x), N where the probability that fatalities overcome a set threshold is considered (fig. 11).

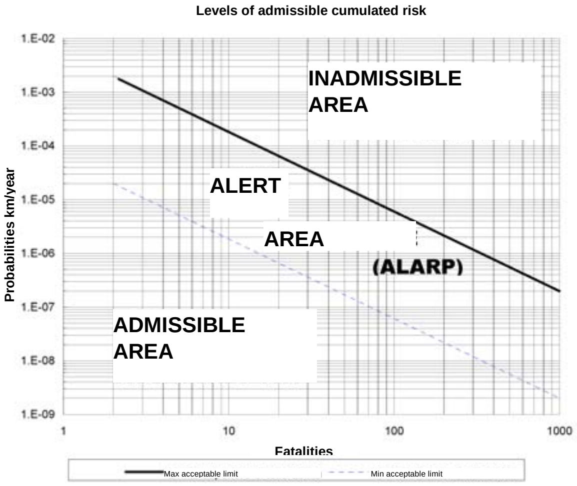

Figure 11 F-N diagram of railway tunnels safety

CONCLUSIONS

The safety design procedure replaces the concepts of accident scenario and of dimensioning event (deterministic analysis of consequences) with the concept of probabilistic group of an escape scenario and of damage expected distribution (probabilistic approach) correlated by a risk flow simulation, and of the escape course of action within a given structure.

Such procedure adopts the clear-cut, analytical IRAM (Italian Risk Analysis Method) risk analysis method, acknowledged as appropriate to define the risk level intrinsic to Italian road and railway tunnels. Moreover, the analysis method provided for represents a reference for the new norms in tunnel safety matters.

Thanks to the systematic approach introduced, it is possible to define the users' rescue rate in possible escape scenarios consequent to accident events considered as critical, and to quantify the risk related to the individual tunnel over a set time-frame.

Such method allows to tackle the safety issue in engineering terms, via a logical sequence of analyses and assessments of numerical and quantitative nature; this avoids that, due to the emotional spur generated by a serious accident, the interventions are excessively allocated, implying a financial burden able to seriously hamper a country's investing capability; therefore it is possible to design the infrastructures' management safety similarly to the design of the works' structural design.

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