Real Time Dynamic Quantitative Risk Analysis Approach for Smart Tunnel

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Abstract

According to the Directive 2004/54/EC and of the Italian transcription Decree 264/06 a risk analysis based design approach is required for tunnel systems for which minimum safety measures does not bring to sufficient safety level. In 2022, the complex systems related sustainability affects each field of study, especially engineering. As konwn, tunnel is a very particular infrastructure in terms of energy consumption and safety issues related to the high level of risk determined by the consequences induced by a potential fire event.

The energy consumption related to the safety systems for tunnel ventilation, traffic management, lighting, and communications is a key point for a sustainable design and requires a new idea of "SMART TUNNEL" in the framework of an holistic approach helps in solving in one time the safety and energy issues.

In order to evaluate the sustainability goals of tunnel safety design, Quantitative Risk Analysis allows to calculate real time risk level due to traffic, meteorological conditions, and the dependability of the safety subsystems, to define the emergency management procedures (emergency planning), for fire extinguishing, ventilation, communication systems and traffic management. This approach allows minimum energy requirements according to the synthesis of sustainable safety requirements. The paper also introduces another concept: GREEN TUNNEL Green is compliant with the production of energy required by means of renewable sources. This article suggests Real Time Dynamic Quantitative Risk Analysis (RTDQRA) in order to verify the compliance to societal acceptability criteria and to territorial resilience target.

Keywords

Real Time risk analysis, safety target, societal acceptability criteria, ALARP, green solutions, emergency planning, smart tunnel, territorial resilience evaluation.

1. Introduction

The Directive 2004/54/EC highlights the importance to understand what the aim of quantitative risk analysis for tunnels is. In fact, this regulatory action makes the quantitative risk analysis mandatory for tunnel that belong of the Trans-European road network (TERN) with special characteristics (traffic conditions, length, geometric parameters). In this case the meaning of the risk analysis approach for tunnel safety design does not involve only to satisfy the minimum required criteria. Risk analysis must be a design tool that does not arise only from some parameters that are fixed but from monitoring real time conditions. The sense of Real Time Dynamic Quantitative Risk Analysis, that can be named with the acronym RTDQRA, is to overcome prescriptive approaches and to adopt a specific study for every single tunnel for the different phases of its life: Design, Construction, Operation, Revamping. Tunnel is a confined space with shows a singular behavior in case of fire, in terms of the propagation of toxic products, soot and demand of safety requirements for users evacuation. Smart tunnel in this perspective means to make system not only with regards to technological design (for example, adopting green energy and smart communications) but also as a tool for life and structures safety: real time analysis gives the opportunity to keep the same level of safety of the tunnel, monitoring and collecting the instantaneous data and make high reliability of the mechanical, electronic and energetic system. The continuous improvement of technologies allows road tunnels to become smart in the sense of using the real time data correlation to be compared with quantitative risk analysis results. Achieving all this improvement, the Smart tunnel becomes a resilient infrastructure.

In engineering field resilience can be defined as the capacity of a material to show an elastic behavior under the load effect without being subjected to permanent deformation. This property is fundamental for materials because when the material commutes his field of deformation in plastic behavior it can't come back to the elastic one. Starting from this simple concept it's possible to explain the resilience of tunnel infrastructure. When a fire event occurs, the tunnel must have the capacity to withstand and guarantee the people and the structuralsafety.
Quantitative risk analysis is already a dynamic method because it is refereed to time dependent data, given from the historical series of events but suitable to ensure the stationary hypothesis for the observed phenomenon. The purpose of real time data is improving the risk analysis adopting the automatization of technologic tunnel tools (smart system) in order to collect a large volume of data that makes the risk based analysis effective for the aim of safety design. A large volume of data is composed of specific ones that are required to implement the risk calculation: real-time weather data, traffic data, territorial data to investigate hazardous factors that may affect the specific infrastructure (see Figure 1).

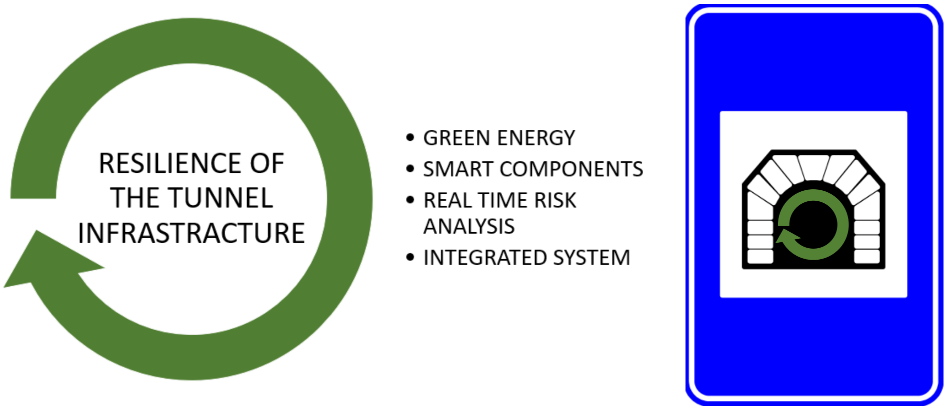

Figure 1 Resilience model of road tunnel

1.1 Objectives

This paper offers an initial overview of the method for quantitative risk analysis and defines the steps to implement a Real Time Quantitative Risk Analysis applied to a road tunnel in order to ensure resilience and sustainability in terms of energy consumption and safety target. It is described, therefore, the collection and processing of the large volume of data derived by smart tunnel monitoring.
In smart tunnels a multiplicity of smart sensors provide a continuous data flow that is analyzed by means of algorithms implemented on the basis of theoretical regression equations. Continuous data flow need continuous energy to power the sensors, the data acquisition system, safety and mechanical systems: this implies a large energy consumption. In order to provide resilient tunnel the energy should be supplied through renewable energy exploiting the natural weather conditions near the tunnel and the operational status of the tunnel. This requires technologies that provide energy and its storage.
As a result the tunnel grows a SMART and GREEN infrastructure and provides an high safety level for the users.

2. Literature Review

From literature it is possible to find method on how Quantitative probabilistic risk analysis can be performed: the first phase is the characterization of the tunnel in terms of parameters and system features but also the accident rate. Fault Tree Analysis (FTA) is usually adopted to represent the physical system not operating as a logical diagram with a top down deductive analysis in which the causes of an event are deduced The FTA includes a visual model of how systems failure, human error and external factors could contribute to an accident or event (Baig et Al,2013). The principal goal of FTA is identifying the potential hazard chains starting from root causes and characterize the Initiating Event (IE) in terms of her probability of occurrence.
The Event Tree Analysis (ETA) allows, starting from IE, to calculate the probability of hazardous scenarios.
The quantification of the population exposed to hazard flow and the definition of fatality function defines the damage as number of fatalities. Consequently it is possible to calculate the risk indicators and to make comparisons referring to a risk acceptability criterion (e.g. ALARP, according to Italian Decree 264/06).

The safety measures that mitigate the damage, allow more time available to external rescue services in case of an hazard scenario like a fire event. The key point of the Decree is integrating the safety systems required for helping the self-rescue when a fire event occurs (ventilation, communication, automatic shutdown, emergency lighting) with the renewable energy in order to increase the reliability of the system. With green power and technological innovation to optimize projects by improving their cost / benefit ratio or to obtain exemptions from prescriptive requirements that are not compatible with the real context of the works. In fact, the aim is to build reliable plants and systems whose performances are subjected to a well performed risk analysis.

The basic contribution of the Decree proposes both prescriptive minimum safety requirements and quantitative risk analysis. 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 Complementary Cumulative risk Distribution (CCD). The tunnel design meets the safety requirements imposed by the standard where the risk indicators assume 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). (Lombardi et Al., 2015).
The consistency and stability of the probability derives from the partition of the Event tree analysis with the composition of the system correlated to the evolution of the accident.

The tunnel management system must monitor all the systems related to the tunnel in maintenance, in the sense of continuity of the service. For this, also the PLC system must coordinate all the system and give results of several different tunnels. The necessity to adopt risk analysis and harmonize this method with the mechanical systems management and the requirement, in terms of energy of the tunnel. The purpose SMART means the following issue to be developed in the tunnel infrastructure: first, implement safety level and safety requirements in smart terms to prevent hazard or control situations in a very short time (3- 4 minutes); in the long period, monitoring level of structural conditions of the infrastructure to optimize the maintenance of the structure itself (Anas, 2018). This is obtained by creating a sensor network which has redundancy along the entire length of the tunnel with different sensor types (see Figure 2):

- TRAFFIC: average speed of vehicles, volume flow and congestion.
- FIRE DETECTION: smoke detector , combustion products concentrations, temperature sensors.
- WEATHER: wind speed and direction, temperature, pollution.
- LIGHTING: light intensity.

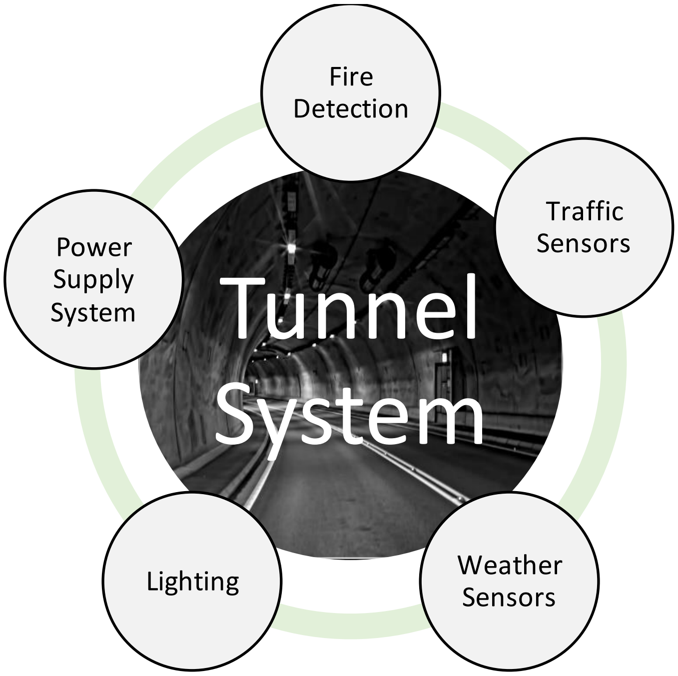

Figure 2 Resilience model of road tunnel

The smart tunnel system works in active mode when a fire event actually occurs, being a tunnel as critical as we have described, giving information and continuous control for ordinary work but moreover for emergency services, especially for smoke extraction, and fire-extinguishing equipment. (Isam et Al, 2020)

3. Methods

The figure 3 explains the concept of the Real time Risk Analysis, **RTDQRA**.

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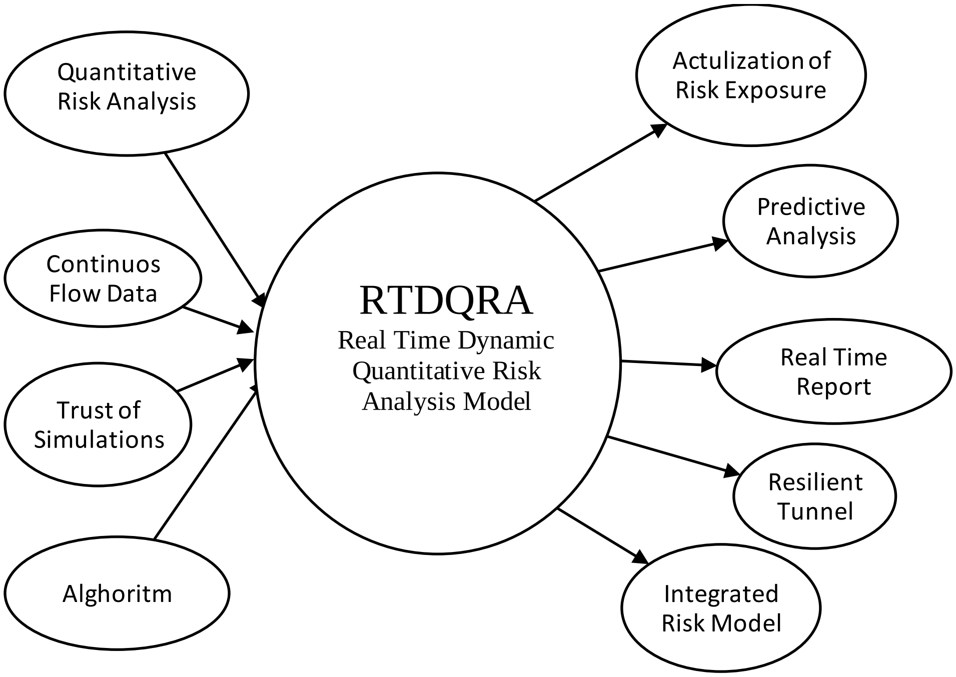

Figure 3 Real Time Dynamic Quantitative Risk Analysis model

First, is necessary to understand why it’s helpful to associate the time scale and risk analysis. In a risk analysis the first step is to identify the potential hazards; then characterize the scenarios thanks to the probability methods using bow tie model trough event tree analysis and fault tree analysis.

Event tree analysis gives several scenarios that are discreet partition of probability density. The risk analysis, through the logical-sequential reconstruction of a structured flow of events, allows to view the evolution of the danger starting from the Constituent Events (causes), which has an Initiating Event (EI), up to the damage.

The critical initial events are determined by pre-conditions (root causes) and can evolve according to the surrounding conditions (contributing causes) and the possible presence and effectiveness of protection, mitigation, and facilitation systems (in short, modulators of the flow of danger), to end-of-emergency scenarios characterized by different levels of hazard on which the severity of the expected consequences (effects) depends on the exposure and vulnerability of the exposed goods. The summary of the proposed model is represented by quantitative risk indicators which, in order to comply with the criterion, in the case of risk for people life, will be estimated starting from the Expected Value of the Damage that allows the determination of the Individual Risk.and Societal Risk, which is evaluated by means of the Back Cumulated risk Distribution (BCD).

The Individual risk (probability of death of the exposed person, referred to annual exposure) is evaluated considering the level of exposure of the area involved as a normalization factor to be applied.

This logical-structured representation of the sequence of events is explained by considering the critical initiating event as a nodal point between causes and consequences.

The consistent and stability of the final indicators of the risk analysis depends on the number of simulations done for the construction of the Event Tree Analysis. Basically, the concept of trust of simulation is linked to the maximum

likelihood estimation criteria: this method determines the statistic inference which is characterized by the hazard rate. (BahooToroody et Al., 2019).
Representativeness of indicators developed by the risk analysis process like synthesis of the work which detects the complete group of scenarios fitting the Initial Event is supported by the computational capacity of the simulator (in case of fire event, Computation Fluid Dynamics simulator, called CFD) available as good as the boundary conditions are realistic and compliant with the maximum likelihood criteria.
Simulations must be prepared referring to the data of the historical series. Sometimes, data are not consistent for the analysis. The sense of creating a model for data collection and consequent variation (updating) of information.
In this model uncertainty is linked to the state of information: without an adequate model, the data are useless.

Thanks to the real data in real time the report of emergency and maintenance conditions allows the actual determination of the risk exposure for users and infrastructure.
Aim of all these concepts described is to realize an integrated risk model which embraces safety measures, structural maintenance, and reliability of the components.
Risk analysis, therefore, has different time scales depending on the goal it is setup for such as design, operation, emergency management, maintenance. An unique risk model can be adapted to the different time scales in order to provide the information that allow to optimize the process.

4. How to make correct Data Collection

Collecting data is fundamental for making the real time quantitative risk analysis in the correct way.
But first data must be prepared fitting the purpose of data collection. Thanks to the sensors which have different characteristics it is possible to provide a continuous flow of consistent data which gives report of traffic, weather, maintenance of structure, operation of systems. The collection of large volume of data represents a real situation of the status.
Using an algorithm, as we have introduced in the previous paragraph, allows to the large volume of data, derived from sensors, to provide relevant information usable to manage activities of the tunnels. In particular the restoration of any degradation, and speed up reply about mechanical reliability. This can be done thanks to the creation of a regression algorithm capable of acquiring data from the tunnel sensors and made detection of faults. (Coccia et Al.,2021).

Smart weather monitoring test system

Smart sensors located nearby the tunnel portals allow the monitoring of the main safety parameters for the tunnel exploitment. At the same time those parameters are relevant for renewable energy production. The parameters monitoring allows by one side to evaluate the tunnel risk level by means of the Real time Risk Analysis and on the other side to evaluate the parameters for the optimization of the energy production. In particular a combined monitoring of wind speed and direction and light intensity provides the parameters to evaluate the ventilation efficiency in case of fire, the external light conditions that affects the lighting at the tunnel portals but also allows the evaluation of the efficiency for wind turbines and photovoltaic systems to be installed at the tunnel portals.
The research project has set up a smart combined sensors by means ultrasonic anemometers and light sensors with a proper data acquisition system that will provide suitable data for smart tunnel software (see Figure 3).

Figure 3 - Light sensor and anemometer

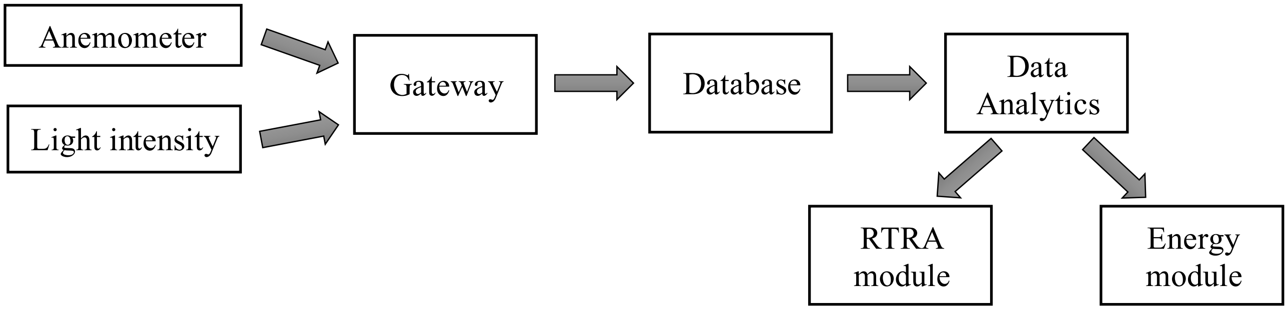

Figure 4 – Flow-chart of data acquisition and analytics

The data collected by a gateway are sent to a database and in parallel analyzed in real time by regression model and sent to the Real Time risk module and to the Energy module (see Figure 4). The Real time risk calculates the ventilation efficiency in case of fire and the car accident probability due to the traffic level and the light intensity and derives the related risk values. The Energy module calculates the ventilation efficiency due to the wind and traffic conditions, the potential energy production by using the jet fans as generators and by a wind turbine installed at the tunnel portals, the theoretical production of the PV panels installed at the tunnel portals. The theoretical energy production is compared with the real energy provided in order to evaluate the system efficiency and to optimize it, also a forecast is made in order to define the correct system sizing and upgrades. In a first phase the PV and wind turbines are not installed and the design of the optimal system is derived by means of data analytics. On another side the normal tunnel ventilation management can be oriented for energy production and or for air quality by means of smart predictive system that manages the fans activation in order to provide the minimum energy consumption.
Also an energy storage is provided in order to use the energy production when is necessary in order to realize a sustainable and autonomous system. The following figure illustrates such a system.

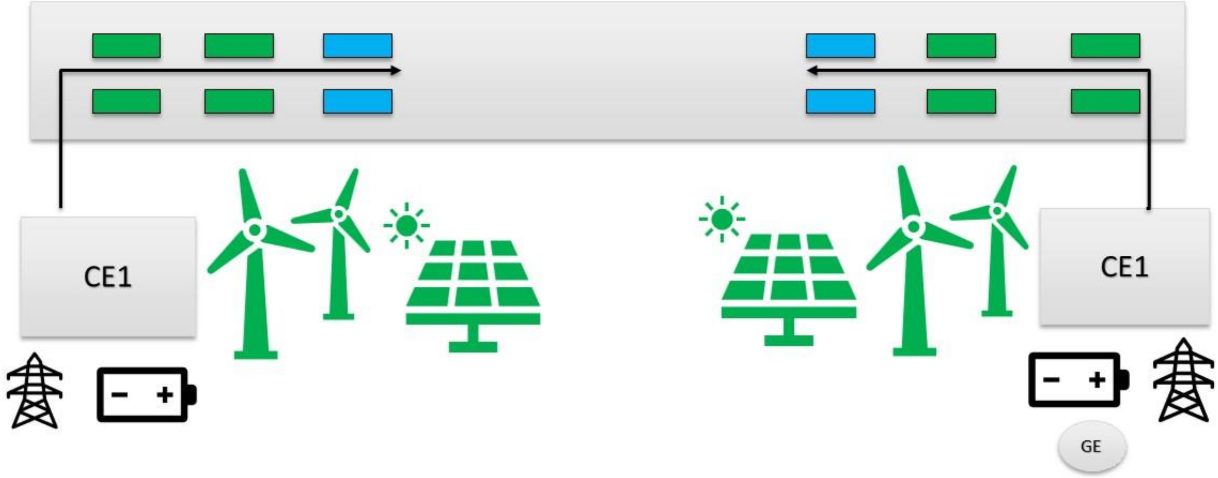

Figure 5 - energy production and storage

5. Discussion

The possibility to create a real time risk analysis model (RTDQRA) and exploit the technologies available with the using of renewable energies determines a risk design-based project of a tunnel, that is actually a critical transport infrastructure. The sustainable goal from the AGENDA 2030 of the United Nations reminds the importance of safety related to the inclusive structure, accessible to everyone with the possibility to improve technologies and communication.

Safety problems related to a critical infrastructure must be, with priority, correlated to the design of the same infrastructure.

Critical does not mean that we cannot do a proper design in terms of safety, but underlines the importance to adopt risk analysis as a design and management criteria in order to give consistency and stability in time.

How to perform a correct estimation? It is necessary to define the sufficient number of the algebraic group composed by disjoined scenarios which represents the total area of the Initial Event (EI). The correct attribution of the probability of the scenarios (which are partition of the EI) means not only to satisfy the conditions of Decree in terms of the required minimum criteria and indicators described in Annex 3 of D. Lgs. 264/2006. In fact first of all, risk associated with a tunnel is defined as the expected value of the damage or as of the probability of exceeding predetermined loss thresholds (BCD reported on the so-called F - N plan). Second the risk concept as the expected value of the damage is obtained as the sum of the products be-tween the probabilities of the individual critical initiator events and the corresponding summation of the probabilities of the terminal events of the individual branches of the events multiplied by the corresponding damage indicators expressed in number of victims normalized to the year. Third, the concept of the risk as a distribution of the probability of exceeding predetermined damage thresholds is shown graphically on the F-N plane.

The F-N plane, F indicates the probability of exceeding the threshold and N the number of fatalities from the BCD (probability of exceeding the damage thresholds) obtained in correspondence with the values of the damage indicators associated with the individual branches of the event tree diagram.

6. Conclusions

This paper gives an overview of the aspects which provides a resilient tunnel infrastructure. The aim of creating a “smart tunnel” is strictly linked to the real time quantitative risk analysis presented in the paper: the innovation is to merge the risk based design and operation (using RTDQRA) and Smart technologies. The typical smart tunnel system is composed by a set of sensors, a data acquisition and management system, a data analytics system, and a real time risk analysis system.

In this context green energy solutions and optimal management are an advantage for the maintenance of the mechanical and electrical system that operates in normal operation but moreover in emergency conditions.

The same smart tunnel system allows the optimization of safety management process and green power management: the research focus for the future is to design, implement and test on the field reliable analysis models by increasing the size of real data.

Those models must aim to give valuable information to the tunnel operators in order to monitor and manage safety and energy demand of the infrastructure.

References

A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility Brussels, 30.11.2016 COM (2016) 766 final.

Amin M. Challenges in reliability, security, efficiency, and resilience of energy infrastructure: Toward smart selfhealing electric power grid. In: Proceedings of the power and energy society general meeting-conversion and delivery of electrical energy in the 21st century, 2008 IEEE. IEEE; 2008. p. 1– 5.

Baig A., A Ruzli, R. Buang, A.B., Reliability Analysis Using Fault Tree Analysis: A Review, International Journal of Chemical Engineering and Applications, Vol. 4, No. 3, June 2013.

BahooToroody A., Abaei M.M., Arzaghi E., Song G, De Carlo F., Paltrinieri N., Abbassi R. On reliability challenges of repairable systems using hierarchical bayesian inference and maximum likelihood estimation,Porcess Safety and Environmental protection , 2019.

Camillo, A., Guillaume, E., Rogaume, T., Allard, A., F. Didieux, F. Risk analysis of fire and evacuation events in the European railway transport network. Fire Safety Journal 60, pp. 25–36.,2013.

Cafaro E. , Saba F. 2013. Approccio Ingegneristico all'Analisi di rischio in galleria. In *Strade & Autostrade* n. 98: 28-35. Milan, Italy.

Coccia Rossana, Corsini Alessandro, Bonacina Fabrizio, Lombardi Mara et Al., An Application of Data-Driven Analysis in Road Tunnels Monitoring, IEOM Society International, 2021.

D. Lgs. 05.06.2006, Road Tunnel Safety

De Ruijter, A., Guldenmund, F., The bowtie method: A review. Saf. Sci. 88,211–218, 2016

European Parliament and Council. Directive 2004/54/EC. Official Journal of the European Union. L.167, Bruxelles, Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32004L0054, April 2004.

Guarascio M., Lombardi M. Rossi G., Sciarra G. Risk analysis and reliability-based design in tunnel fire safety. 575 584. 10.2495/SAFE090531.

Guarascio M. "As Low As Reasonably Practible". How it does work in the rail and road tunnels in Italian rules. Risk Acceptability/Tollerability criteria. The Gu@larp model. SAFE21.

Guarascio, M., Lombardi, M., Rossi, G., Sciarra, G., Risk analysis and acceptability criteria, WIT Transactions on the Built Environment pp.131–138, 2007

Guarascio M., M. Lombardi, G. Rossi, G. Sciarra, Road tunnel safety rules in Italy: the tunnel country,WIT Transactions on the Built Environment pag. 319-326, 2007

Konstantinos A. Kirytopoulos,. Quantitative risk analysis for road tunnels complying with EU regulations. Journal of Risk Research 13(8):1027-1041, December 2010.

Isam Shahrour,Hanbing Bian,Xiongyao Xie ,Zixin Zhang, Use of Smart Technology to Improve Management OF Utility Tunnels, Applied Sciences ,January 2020

IEEE Smart Cities. About Smart Cities. Available online: https://www.ieee-pes.org/pes-communities/ieee-smart-cities (accessed on 8 March 2022).

Lombardi M., Rossi G., Fire protection of emergency electrical devices: effect on the level of risk – a case study of a rail tunnel, WIT Transactions on the Built Environment, Vol 151, 2015.

Paolanti Marina, Felicetti Luca Romeo Andrea, Mancini Adriano Frontoni, Emanuele Machine Learning approach for

Predictive Maintenance in Industry 4.0. IEEE/ASME International Conference on Mechtronic and Embed System and Applications, MESA, 2018.

Report 2008R02EN. 2008. Risk analysis for road tunnels. PIARC

Report 2012R20EN. 2012. Assessing and improving safety in existing road tunnels. PIARC

Report 2012R23EN. 2012. Risk evaluation, current practice for risk evaluation for road tunnels. PIARC

Report 2016R35EN. 2016. Experience with Significant Incidents in Road Tunnels. PIARC

Smart Book, Anas, 2018.

Sun X. & Luo M. 2014. Fire Risk Assessment for Super High-rise Buildings. In *Procedia Engineering* 71: 492 – 501. Elsevier

Biography

Mara Lombardi – currently is Associate Professor at Sapienza University of Rome. She obtains a PhD in Materials and Raw Materials Engineering. She carries out numerous assignments both in the University field and for important national and international Bodies / Structures. She is engaged in teaching activities for various Degree Courses of the Faculty of Civil and Industrial Engineering of Sapienza: SAFETY ENGINEERING AND CIVILPROTECTION, TRANSPORT SYSTEMS ENGINEERING, ENVIRONMENTAL AND TERRITORY ENGINEERING . She has participated and she has been is responsible for several research projects at national level both university and financed by public and private bodies, such as the Municipality of Rome, ATAC, INAIL, Start-up 3-FASE srl and Autostrade per l'Italia SpA. She is member of The research activity focuses on: Fire Safety Engineering, geostatistical analysis and modeling, quantitative risk analysis in relation to human behavior, RAMS approach, risk analysis for complex systems, road and railways network safety and occupational safety. She is currently chairman of the Degree Course in Safety and Civil Protection Engineering, of the start-up Sapienza "Security 4.0" and a member of the CCTS (CNVvF), of the CTR (CNVvF, Lazio Regional Directorate), of the Authority Commettee for road tunnel (ANSFISA) and of INAIL scientific Commettee. She is the author of publications written both individually and in collaboration, many of which are international in character and book chapters.

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