SMART TUNNEL IN INDUSTRY 5.0: IMPROVING ROAD TUNNEL RESILIENCE BY DYNAMIC RISK ANALYSIS

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Abstract

Safety in tunnels is being contemplated through a holistic approach due to accidents that occurred through years. Technological innovations have led to the tunnel concept evolution from civil to technological infrastructure, where technology overcomes the limits of the geometric design, increasing its operating capacity. This paper aims to illustrate SCADRA principles (Supervisory Control Acquisition and Dynamic Risk Analysis), developed thanks to EURAM (EUropean Risk Analysis Method) methodology, which assessed the risk of over 600 road tunnel tubes, focusing on the following values: users and managers' needs (Human-centricity), usage of green technologies and application of energy saving strategy (Sustainability), and improvement of tunnels resilience (Resilience). SCADRA is used in monitoring continuously the tunnel state by gathering the safety influence variables and performing a dynamic risk analysis, quantitative and probabilistic, in real-time. The system was installed in three Italian road tunnels, executing over 130,000 instantaneous risk analyses. The applications' results and the future developments will be presented according to tunnels' safety improvement, maintenance, and management.

Keywords: risk, resilience, tunnelling, real-time, safety

1 Introduction

Italy has an extraordinary formation of its terrain varying from mountains to plains. In order to have an accessible land connection throughout the country that will facilitate the flow of people and goods, the importance of tunnels in road transportation network enters the scene. After the accidents occurred between 1999 and 2001 in Mont Blanc, Tauern and St. Gotthard tunnels, safety in tunnels started to be contemplated through a holistic approach. These events have become a critical issue for politicians and for public, pushing the European Commission to establish the Directive 2004/54/EC [1], which specifically tackles the safety in Trans-European Road Network (TERN) tunnels and aims to guarantee a minimum level of safety to the tunnel users. In Italy, the Directive 2004/54/EC was implemented through the Legislative Decree n.264 of the 5th October 2006 [2], with the purpose of guaranteeing a minimum and sufficient safety level for users in all TERN tunnels, defining a series of minimum safety requirements to be implemented in all tunnels longer than 500 m. The complexity of an underground structure – environment, planning and construction, safety design, operation and management procedures, etc. – and the fast technological advancement have led to the concept of the "tunnel system". Due to the accidental events, the European political response and the engineering technique, safety in tunnels has become a central and complex issue involving: users' behaviour in emergency situations, infrastructure characteristics, and

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operational characteristics, such as type and functioning of the equipment installed, including safety measures. Technological innovations have led to the tunnel concept evolution from civil works to technological infrastructure, where the installed technology overcomes the geometric-functional limits, increasing its operating capacity. The purpose of this paper is to illustrate the fundamental principles of SCADRA system, developed and implemented thanks to EURAM methodology and software [3], which assessed the risk of over 600 Italian road tunnel tubes according to the Legislative Decree 264/06, to present and comment the most significant results obtained and to identify possible future developments, in terms of tunnels' safety improvement and conservation and tunnels' maintenance and management.

2 SMART Tunnel

Smart Tunnel idea [4] comes from the achievement of Industry 4.0, in which there is a strong industrial automation that integrates the most innovative technologies, in order to improve the operating and safety conditions and increase the equipment productivity and quality. Smart Tunnels allow optimal tunnel management during operation and in emergency situations thanks to the installation of traditional and technological sensors and the real-time assessment of tunnels' safety level, as a function of climatic conditions, traffic data and equipment state, in accordance with the Legislative Decree 264/06 [2]. Smart Tunnel together with SCADRA system (Figure 1) allow controlling the systems in the tunnel and improving the effectiveness of the operational and integrative measures increasing the safety of the users and producing also other advantages like energy savings and the improved scheduling of maintenance.

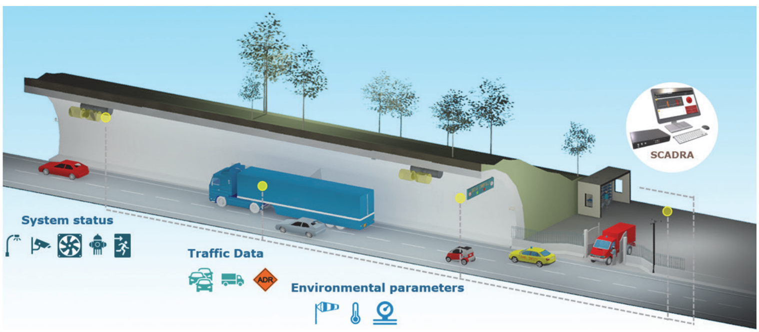

Figure 1 Smart Tunnel with SCADRA

SCADRA system was installed in three Italian road tunnels, executing over 130,000 instantaneous risk analyses in real situations and this report illustrates the main results and the considerations that can be drawn for a correct tunnel management during normal operation and emergency situations (Table 1).

Table 1 SCADRA analyses report

Tunnel	**N. of instantaneous risk analyses executed**	**Analysis duration** [h]
TUNNEL 1	8.640	2.160
TUNNEL 2	92.160	23.040
TUNNEL 3*	28.608	7.152

*Data analysed from 15/10/21 to 10/11/22.

From the results of the first installations, the SCADRA system is proving to be a powerful prevention tool that significantly increases the resilience of road tunnels by:

- real-time risk analysis, since it gathers and analyses data from various sensors, enabling continuous monitoring of safety conditions. By performing DRA, the system can assess the current risk level and promptly respond to any changes or potential threats,
- safety management, based on the results of risk analysis, to mitigate risks and ensure the required safety level within the tunnel,
- preventive maintenance, since SCADRA facilitates it by monitoring the structural and operational aspects. By detecting potential issues early on, it helps reduce the need for reactive maintenance, minimizing downtime and ensuring the continuous operation of the tunnel,
- optimization of emergency response, as it enables proactive decision-making and optimize resource allocation for improved tunnel performance and safety.

Since 2019, the system is installed in tunnels with different structural and technological characteristics and with different environmental and traffic characteristics, and the results are clear and consistent with each other, as shown by the analysis of the data of the first applications.

3 SMART system

SCADRA is a system that continuously monitors the tunnel state by collecting the variables that can influence the tunnel safety conditions (equipment and structures state, traffic data and environmental parameters) and performing a dynamic risk analysis, quantitative and probabilistic, at regular intervals or due to sudden change in the gathered data [5]. If the risk level grows towards the unacceptability threshold or in case of anomalous situations (traffic flows increase, equipment deterioration, etc.), SCADRA activates or signals the necessary safety measures in order to restore the required safety level. Instead, if the risk level is low for a certain amount of time, SCADRA suggests energy saving strategies to perform energy management for the lighting and ventilation equipment [6]. SCADRA configuration sets alongside the traditional "Supervisory Control And Data Acquisition" systems (SCADA), a system of acquisition of all the parameters, that can influence the tunnel management (collecting data related not only to systems fault and malfunctions, but also on traffic type and intensity, dangerous goods and vehicles presence, air quality, visibility, wind speed, etc.) in order to get information on safety systems operating status, on environmental conditions and on traffic status within the tunnel, necessary for the subsequent dynamic risk analysis. Through the elaboration and analysis of all parameters, obtained from sensors and system, a continuous safety level monitoring of the tunnel is carried out, performing the Dynamic Risk Analysis at regular pre-established intervals, under normal operating conditions and in emergency case. The equipment installed elaborates an analysis on a series of external input data. These external input data have been divided into 2 macro categories: fixed inputs, related to the tunnel structure, and variable inputs, that may vary over time (weather, vehicular flow and tunnel systems efficiency, etc.). SCADRA subsystem acquires, as dynamic inputs, the input data and the parameters necessary for its processing, directly from the SCADA tunnel. The information provided by the sensors and the historical data recorded are processed by SCADRA through a specific software in order to execute a risk assessment in real-time and to determine if the risk is tolerable or if it is necessary to implement further safety measures. According to the expected level of risk, SCADRA provides a safety management (Figure 2) that can be used for: planning preventive measures, like reducing speed limits, minimum distance among vehicles and prohibition of overtaking for HGV, and executing protective measures, such as sending communications to users, fire brigade alert, interruption of the systems energy saving mode.

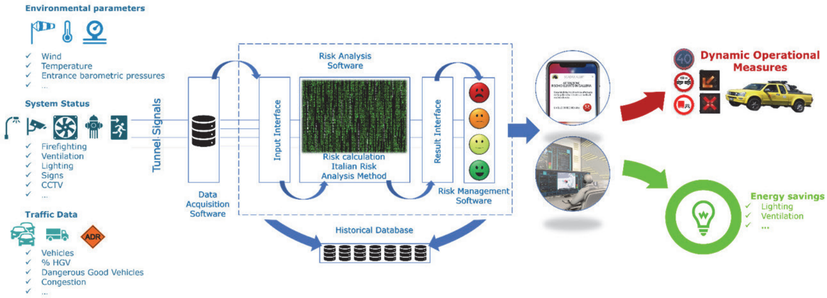

Figure 2 SCADRA system layout

4 Dynamic Risk Analysis (DRA)

SCADRA is based on the Dynamic Risk Analysis (DRA): the data are acquired by technical systems and specific sensors. Afterwards, a processor installed in the server performs the DRA and manages the residual risk (Figure 3).

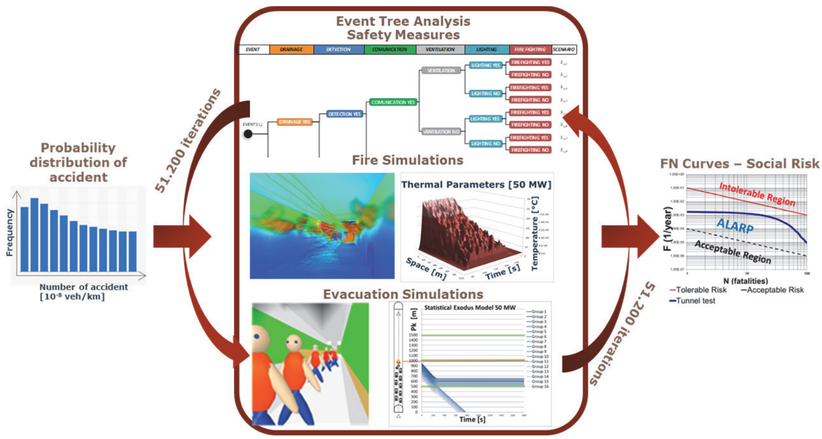

Figure 3 DRA methodology

The DRA results are processed in order to classify the value of the risk according to pre-established levels that allow to undertake the appropriate actions associated with them and envisaged in the risk management plan, and it is normally implemented every 10-15 minutes, during the operation period, and in case of sudden changes of traffic or environmental conditions and operating level of safety systems. The risk value is obtained by executing the quantitative probabilistic analysis, according to the method defined by the Italian Law (Italian Risk Analysis Method - IRAM), and the results are represented by the Live Expected Value of Damage (LEVD) and the F-N Curve, which defines the social risk. The tolerability and acceptability criteria are settled by evaluating the risk level in real time (LEVD) and by comparing it with the reference value, assessed during the tunnel design and approved by the Administrative Authority. If the real-time risk becomes relevant, SCADRA starts to manage the technical systems and to introduce effective safety operational measures that can reduce it. The risk level has been classified according to 4 categories of instantaneous risk: Level 1 - Low risk level, which corresponds to optimal safety conditions (Possibility to enable the energy saving mode), Level 2 - Normal risk level (Standard safety conditions), Level 3 - Pre-alert level, and Level 4 - Alert level.

The risk levels are represented by a graphical interface, which shows different coloured emoticons according to the real-time risk level. The graphical interface shows the LEVD trend related to the surveys taken in the last 24 hours and it highlights the significant deviations of the input parameters. A browser-based graphical user interface was developed in order to be user-friendly to facilitate the control centre operator in the real-time risk level monitoring and to easily understand the causes behind the risk level increase and to quickly decide on the necessary safety interventions.

5 SCADRA and road tunnel resilience

Tunnel resilience has been defined, by PIARC Technical Committee 4.4 "Tunnel" [7], as "The ability to prepare and plan, resist / absorb, recover or adapt more successfully (promptly and efficiently) to the actual or potential negative effects of events or developments affecting the use of a tunnel. In this context, an acceptable level of safety is an essential constraint for the availability of the tunnel". SCADRA system installation perfectly fits within improving road tunnel resilience, since it is always possible to know in real-time what happens inside the tunnel, the environmental conditions, the traffic data and the system status. Therefore, SCADRA allows to monitor continuously the tunnel risk level (Figure 4) and, if needed, to apply operational measures with the purpose of ensuring the required safety.

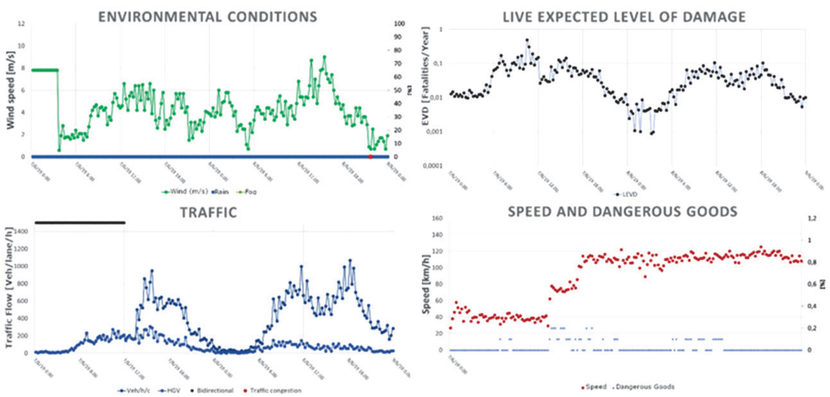

Figure 4 Data collected and analysed by SCADRA

Consequently, the system supports the increasing of the road tunnel resilience by preventing and planning safety measure according to every critical situation that might occur. SCADRA system can also represent an effective optimization for the firefighters' management, in order to reduce the instantaneous residual risk in critical conditions, such as congested traffic in a tunnel with longitudinal ventilation. Furthermore, through the continuous acquisition and processing of data, it is also possible to have preventive maintenance focused on user safety, with the aim of reducing interventions, operating costs, intervention times, MTTR (Mean Time To Repair), and system(s) unavailability. Therefore, SCADRA system allows to operate and manage technical systems improving the effectiveness of operational and integrative measures, by enhancing the maintenance design and planning and considering the users' safety.

6 Installation results

SCADRA implementation is quite simple: an industrial PC is installed in the main technical room and connected with the SCADA system and all the necessary sensors. The software installed in SCADRA allows the DRA execution. SCADRA cost is compatible with a SCADA system cost, but the obtainable benefits from SCADRA are remarkable as described in the previous paragraphs. In fact, SCADRA has already been successfully installed in unidirectional road tunnels in operation, with different structural and technological characteristics and diverse environmental and traffic characteristics. Figure 5 shows the LEVD trend calculated by SCADRA system in real-time for the three tunnels for a period of four days.

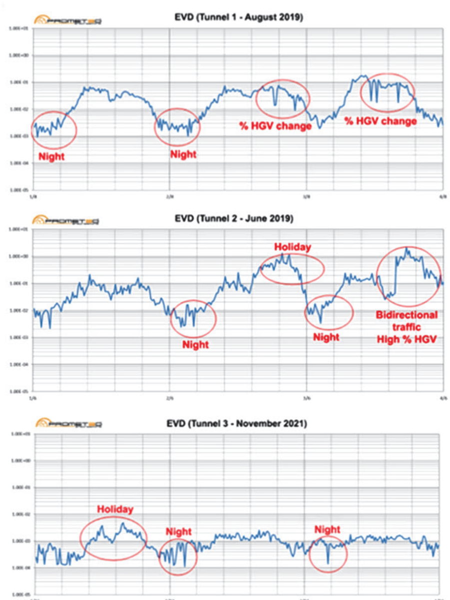

Figure 5 Data collected analysed by SCADRA

It is interesting to observe the excellent consistency of all the data and the risk trend in the different situations which for each tunnel are absolutely different from each other both in terms of type and intensity / severity.

7 Conclusions and future challenges

Increasing tunnel resilience is mainly achieved through the search for a continuous improvement in safety during the tunnel operation, by applying the dynamic monitoring of the risk conditions in the tunnel through SCADRA, and targeted maintenance which takes into account the ageing of construction materials and the interaction with the environment, which can endanger infrastructure stability and functionality, as well as the users' safety. The current technical and technological progress in the field has enabled the safety achievement, for this reason SCADRA system can be considered a powerful prevention tool that should be integrated in all types of tunnels to increase their resilience. From the applications examined, it has been seen that this system is also suitable for existing tunnels by exploiting innovative low-cost technologies and improving safety in old tunnels thanks to operational measures integrating the systems and, if necessary, replace the lack of requirements.

Italy is the European country with the largest number of tunnels, with about 650 km of road tunnels in operation on TERN and, worldwide, Italy is second only to Japan for tunnel equipment. Over 600 tunnels many of which were built before the 90s in often very poor soils. This particular feature requires special attention to the theme of resilience of underground works. Therefore, the topics of safety in operation, of a correct structural and plant maintenance and the monitoring of a tunnel play a fundamental role to increase its ability to react or adapt more successfully to the negative effects of events, actual or potential, which affect the tunnel usage. SCADRA demonstrated to be a supplementary prevention and safety measure for the tunnels management, both during normal operation and in emergency conditions, capable of guaranteeing real-time monitoring of the tunnel risk level. Future developments foresee that SCADRA will also be able to monitor the structural state of the tunnels and any other structures, such as bridges, viaducts, as well as the presence of any landslides in the surrounding environments. The expansion of SCADRA's capabilities will involve the integration of additional sensor systems and advanced monitoring technologies. The system will need to incorporate a variety of sensors capable of monitoring different aspects of infrastructure health. These sensors include strain gauges, accelerometers, displacement sensors, and corrosion sensors for structural monitoring, as well as environmental sensors for detecting factors such as temperature, humidity, and precipitation. SCADRA will gather data from the newly integrated sensors, as well as existing monitoring systems, and this data will be integrated into a centralized platform for real-time analysis and decision-making. The system will use advanced analytics and algorithms to process the incoming data and assess the structural health and environmental conditions, involving machine learning techniques for predictive maintenance, anomaly detection algorithms for early warning of potential hazards, and risk assessment models for evaluating infrastructure resilience. Therefore, SCADRA will require robust communication networks to ensure seamless connectivity between sensors, data processing systems, and decision-makers. This may involve leveraging existing communication infrastructure or implementing dedicated networks for real-time data transmission.

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