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

[1]Alessandro Focaracci, [2]Francesca Zacchei, [2]Luigi Martirano

[1]Prometeoengineering.it S.r.l., IT
[2]La Sapienza - University of Rome, IT

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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: Dynamic Risk Analysis, Smart Tunnel, Real-time Monitoring, Infrastructure Resilience

1. INTRODUCTION

Italy's diverse geomorphological landscape, extending from mountains to plains, has made road tunnels essential for ensuring continuous and efficient national connectivity. Following the major accidents in the Mont Blanc, Tauern, and St. Gotthard tunnels (1999–2001), tunnel safety evolved toward a systemic and integrated approach, leading to the adoption of Directive 2004/54/EC and its national transposition through Legislative Decree No. 264/2006, which established minimum safety requirements for all TEN-T (Trans-European Transport Network) tunnels. This shift introduced the concept of the "tunnel system," where safety results from the interaction between infrastructure design, user behaviour, and operational control systems such as ventilation, lighting, communication, and fire protection. Advances in digital and automation technologies have transformed tunnels from civil works into intelligent infrastructures capable of real-time monitoring and adaptive management. Within this framework, the SCADRA system (Supervisory Control Acquisition and Dynamic Risk Analysis), developed according to the EURAM methodology, has been applied to over 600 Italian tunnels, providing real-time, risk-based safety assessment and marking a significant step toward data-driven, resilient, and sustainable tunnel management. The present paper illustrates the fundamental principles of the SCADRA system (Supervisory Control Acquisition and Dynamic Risk Analysis), developed and implemented using the EURAM methodology and software [1], which has been applied to assess the safety level of over 600 Italian road tunnel tubes in accordance with Legislative Decree 264/06. The paper discusses the most significant results obtained, evaluates the system's contribution to safety improvement and infrastructure resilience, and outlines future developments for the enhancement of tunnel management, maintenance, and operational sustainability.

2. SMART TUNNEL

Smart Tunnel idea [2] 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 No. 264/2006. 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.

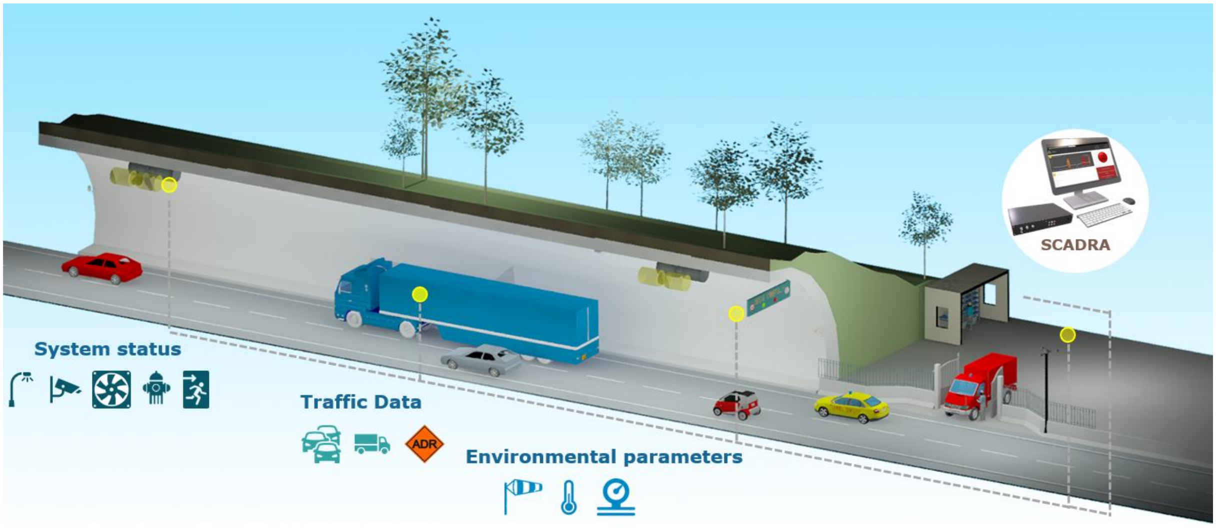

Figure 1: Smart Tunnel with SCADRA

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.

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 [2]. 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 system [3].

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.

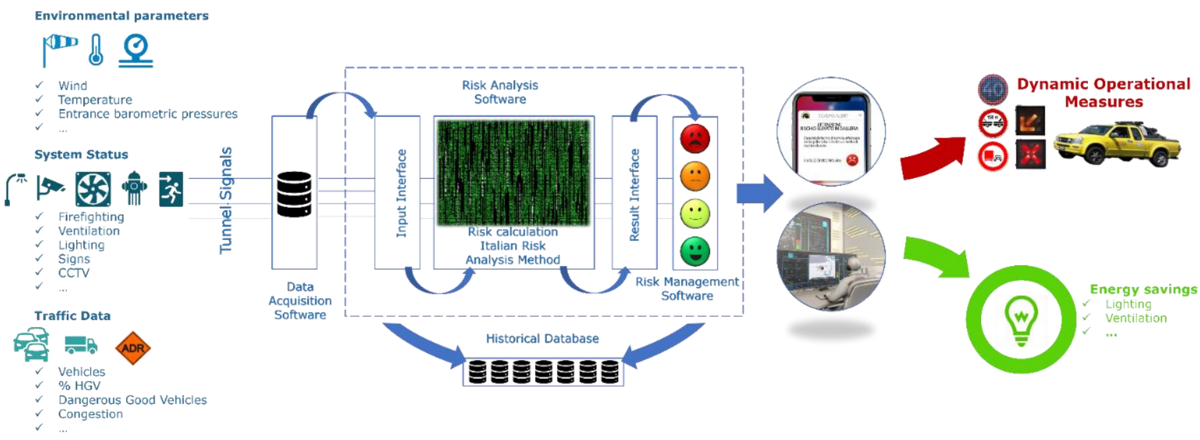

Figure 2: SCADRA system architecture

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).

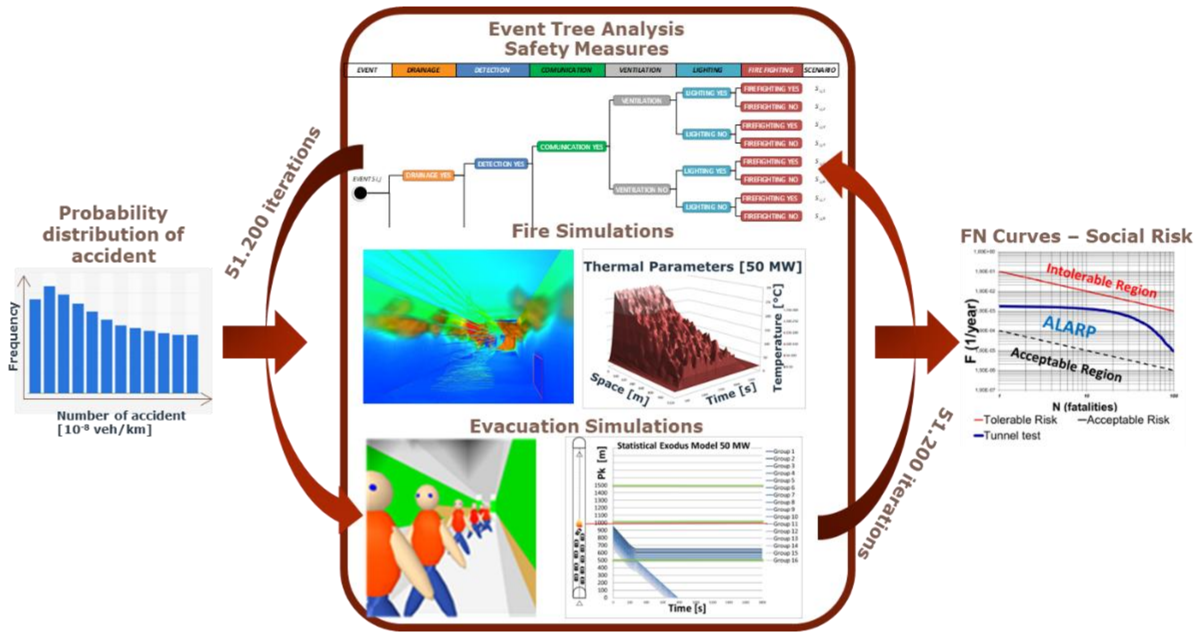

Figure 3: DRA methodology

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: LEVD well below reference values; energy-saving mode enabled;
- Level 2 – Normal Risk: standard operational safety;
- Level 3 – Pre-alert: increased LEVD; preventive measures suggested;
- Level 4 – Alarm: LEVD exceeds acceptable threshold and emergency measures are activated.

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" [4], 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 (instantaneously or by defining regular intervals to calculate the risk level) 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.

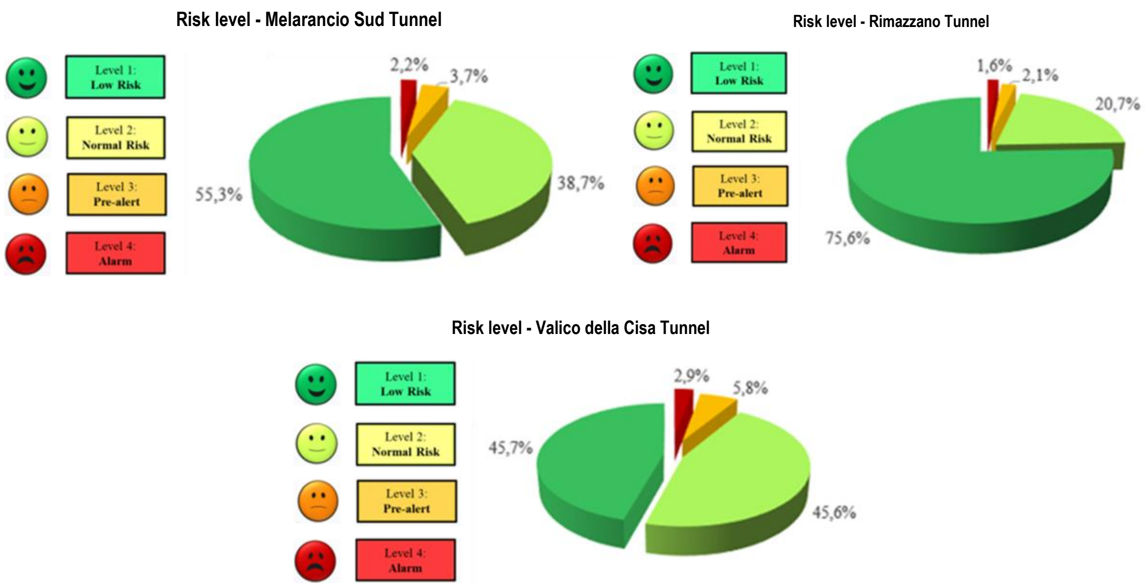

Figure 4: Risk Levels calculated by SCADRA system

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.

5.1. Risk Influencing Factors

Risk Level 1 corresponds to optimal safety conditions, where the calculated Expected Value of Damage (EVD) remains significantly below the admissible limit established during the design phase. Under these circumstances, the system may authorise energy-saving strategies without compromising tunnel safety.

Key influencing factors typically associated with Risk Level 1 include:

- Low or moderate traffic flow, particularly during off-peak and night-time hours;
- High availability of safety-critical systems, including ventilation, fire-fighting installations, emergency signalling and communication systems;
- Favourable environmental conditions, such as normal visibility and stable meteorological conditions;
- Absence of critical alarms or operational anomalies in electromechanical and monitoring equipment.

Under Risk Level 1, the system may therefore recommend energy-saving actions by regulating technical systems to function at reduced operational performance compared with normal operation, without any compromise to safety requirements. Activation of this operating mode is permitted exclusively under optimal safety conditions, corresponding to a High Safety Level, thereby guaranteeing that the adoption of energy-saving measures does not produce any increase in risk beyond acceptable thresholds [3].

Risk Level 2 is representative of ordinary operating conditions, with values of risk slightly higher than in Level 1 but still well within the acceptable safety margin.

- Typical contributors to Level 2 behaviour include:
- Increased but still regular traffic volumes, including modest fluctuations in HGV share;
- Minor degradation or temporary unavailability of subsystems, without significant impact on global safety performance;
- Non-severe variations in environmental conditions (e.g., moderate temperature variations, low-intensity precipitation);
- Transient operational adjustments, such as maintenance switching or subsystem testing.

Risk Level 3 corresponds to a pre-alert condition, requiring heightened attention and, where necessary, preventive operational measures to maintain safety.

Observed triggers associated with Level 3 include:

- High traffic flows approaching design capacity, particularly during weekends and holiday peaks;
- Elevated proportion of HGV, generating increased fire load and impacting evacuation/ventilation dynamics;
- Combined minor inefficiencies in multiple systems, which, although individually insignificant, collectively influence the risk level;
- Transient anomalies in ventilation, fire-detection or communication systems;
- Adverse micro-climatic conditions or portal-effect phenomena with higher temperature gradients or smoke-stratification risk.

Risk Level 4 indicates a high-risk condition, requiring immediate operational action to ensure safe tunnel operation. Although rare during the monitoring period, Level 4 scenarios are critical for evaluating the system’s responsiveness.

Typical situational drivers observed or simulated for Level 4 include:

- Simultaneous degradation/unavailability of safety systems, such as ventilation combined with emergency communication or fire-fighting system faults;
- Severe operational or environmental anomalies, including forced simulation conditions applied during system validation tests;
- Traffic conditions beyond anticipated thresholds, particularly when combined with system malfunctions or abnormal heavy-vehicle shares;
- Rapid parameter variations, requiring SCADRA to recompute the risk and recommend immediate mitigation measures.

Overall, the results of SCADRA applications clearly demonstrates the capability of SCADRA system to discriminate between different operational safety conditions and to reliably identify the key drivers influencing real-time risk evolution. Across all monitored scenarios - from optimal operating states to high-risk conditions - SCADRA consistently responded to variations in traffic intensity, subsystem availability, and environmental parameters, providing timely and accurate risk-level classification.

The progressive escalation of influencing factors across the four risk levels confirms the importance of adopting an integrated monitoring framework, in which traffic conditions alone are insufficient to characterise tunnel safety. Instead, the results highlight the necessity of evaluating the combined contribution of structural, technological, operational and environmental elements, validating the holistic approach underpinning SCADRA.

These findings reinforce the robustness and operational maturity of the system, demonstrating its effectiveness as a real-time decision-support tool for tunnel risk management. By enabling proactive responses and supporting energy-optimisation strategies under safe conditions, SCADRA represents a substantial advancement in the evolution from static, design-based safety assessment towards dynamic and intelligent tunnel-safety management.

5.2. Risk Consideration: Analysis of LEVD Variations

The monitoring data recorded demonstrate that the calculated risk level increases in conjunction with traffic peaks, particularly during typical weekend travel periods. As shown in Figure 5, this behaviour is highlighted by the red circles marking Easter Monday (18/04/2022) and during the Liberation Day holiday (25/04/2022). On both dates (red circles), the traffic volume reached approximately 60.000 vehicles/day, a value comparable to the tunnel’s design traffic assumptions. Under such conditions, the inefficiency of even a single safety-critical subsystem could temporarily result in a risk level comparable to or exceeding the static design LEVD value.

Nevertheless, even for Average Daily Traffic (ADT) values close to design conditions, the measured risk remained below the design LEVD, as the static risk assessment performed during the design stage already accounts for an admissible margin of subsystem unavailability.

This trend is expected, as a clear correlation exists between traffic flow (approximately 30.000 vehicles/day during the analysed weekends) and the increase in the calculated tunnel risk level. However, the risk level does not depend solely on traffic volume nor follow a strictly linear relationship. LEVD fluctuates as a function of multiple interacting parameters, including:

- Traffic conditions;
- Environmental conditions;
- Availability and performance of safety systems.

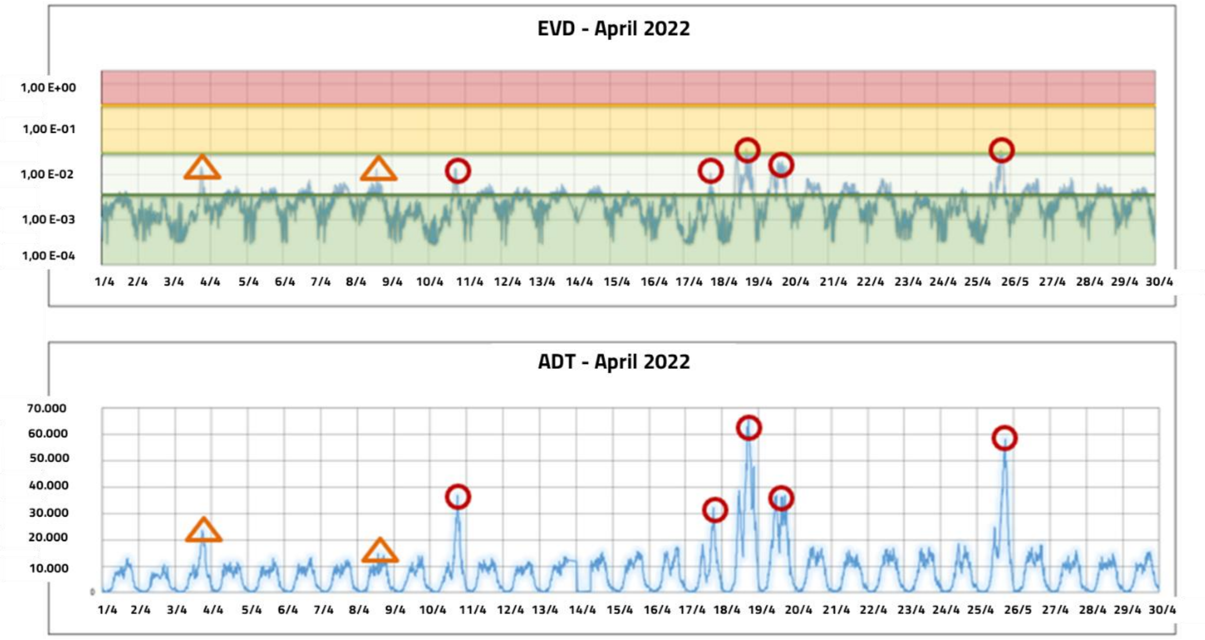

Figure 5: SCADRA system results (April 2022)

Overall, despite traffic variations and forced-input simulations, the calculated risk values consistently remained well below the design LEVD, indicated by the horizontal green reference line in the graph.

The correlation between LEVD and ADT, indicates that while traffic volume influences risk, other factors - such as system availability, environmental stability, and heavy-vehicle percentage - play decisive roles in determining the instantaneous safety level. SCADRA's multi-parametric model allows for a holistic representation of tunnel risk evolution, providing decision-makers with a reliable and actionable framework for dynamic tunnel management.

6. SUMMARY AND CONCLUSION

The analysis of SCADRA installations demonstrates that the system provides a robust, scalable, and adaptive solution for modern tunnel safety management. By integrating continuous data acquisition, probabilistic risk computation, and decision-support functionalities, SCADRA enables a transition from prescriptive design safety to proactive, data-driven governance. Its ability to manage residual risk, detect anomalies, and implement energy-saving measures under safe conditions positions it as a cornerstone technology within the Industry 5.0 framework.

Future developments will focus on extending SCADRA's application to metro and railway tunnels, integrating artificial intelligence for predictive risk modelling, and connecting the system with digital twin platforms for real-time simulation and training. These advancements will further enhance human-centricity, sustainability, and resilience—the three defining pillars of Industry 5.0.

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