



## **AI & SMART TUNNEL: IMPROVING ROAD TUNNEL RESILIENCE BY DYNAMIC AND PREDICTIVE RISK ANALYSIS**

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### **Abstract**

Technological innovations have led to the tunnel concept evolution from civil works to technological infrastructure, where technology overcomes the geometric-functional limits, increasing its operating capacity. Today, the tunnel system must have the ability to adapt to a scenario in which transportation is based on guided or self-driving cars, with internal combustion engines or electric motors, that safely run through Smart Roads and Smart Tunnels. This implies that the tunnel system must be part of “Intelligent Transport Systems” (ITS), a goal introduced by Directive 2010/40/EU [1]. This paper aims to illustrate the fundamental principles of SCADRA (Supervisory Control Acquisition and Dynamic Risk Analysis) system, developed and implemented thanks to EURAM (EUropean Risk Analysis Method) methodology, and how it can be empowered thanks to Artificial Intelligence (AI). SCADRA system is a supplementary prevention and safety measure for tunnels management, both during normal operation and in emergency conditions, capable of guaranteeing a real-time monitoring of tunnel risk level. Thanks to AI, the system can be enhanced in order to execute a predictive risk analysis, by assessing the tunnel risk level trend according to the data gathered and by adjusting the next prediction to the real-time risk data. Artificial Intelligence (AI) and the Generative AI (Gen AI) are concepts and areas of practical application that are quickly growing, in terms of interest, products and services across multiple sectors. The concept is also relevant to the road, transport and mobility sectors in areas such as infrastructure design, operations and management, but it could be crucial for the safety aspect.

*Keywords: risk, resilience, tunnelling, AI, safety*

### **1 Introduction**

With the development of digital technologies, tunnels have been equipped with technical safety systems designed to ensure constant operation and adaptability under different and critical conditions, pursuing goals of energy efficiency, cost minimization, and environmental impact reduction. The installation of automation systems based on programmable logic controllers, connected to supervisory and operational control centres, has ultimately ensured the coordination and integration of action across all subsystems, providing necessary data to understand traffic conditions, the status of operational and safety systems, and to efficiently manage anomalies and emergencies. The aim of this paper is to illustrate the key points of SCADRA (Supervisory Control Acquisition and Dynamic Risk Analysis) system, developed and implemented thanks to EURAM methodology and software [2], and how it can be empowered thanks to Artificial Intelligence (AI).

## 2 SMART Tunnel

The “Smart Tunnel” concept is part of the “Industry 4.0” vision, with a strong industrial automation that integrates the most innovative technologies (integrated memories, wireless sensors, integrated actuators and intelligent software) in order to improve operating conditions, increase productivity and quality installations. Smart Factory is the key concept of this 4<sup>th</sup> industrial revolution and defines a totally new approach to the industrial world, based on dynamism and optimization of production performance developed in three key concepts: Smart Production, Smart Service and Smart Energy. The creation of an innovative tunnel safety management system with dynamic risk analysis, is part of this context, encouraging cooperation between machinery, operator and tools (Smart Production), through the connection between physical infrastructures and IT infrastructures (Smart Service) and through the implementation of energy saving (Smart Energy). In traditional tunnels, sensors (like smoke meters, anemometers, luminance photometers, etc.) are mainly used to control systems, to detect and measure some physical effects and to send the information to controller in order to regulate the system. Smart Tunnel, through the installation of traditional and advanced sensors and real-time evaluation of effectiveness according weather conditions, traffic data and system status, allows an optimal management of the tunnel and the realization of many operational measures knowing in real-time the real effectiveness of safety systems. The Smart Tunnel enables optimal tunnel management during operation and emergency situations by incorporating traditional and technological sensors, real-time assessment of tunnel safety levels based on weather conditions, traffic data, and system status, in accordance with the provisions of Legislative Decree 264/06 [3].

## 3 SCADRA (Supervisory Control Acquisition and Dynamic Risk Analysis) 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. 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 [4]. Smart Tunnel together with SCADRA system [5] allow controlling the tunnel systems and improving the effectiveness of the operational and integrative measures, by increasing the users’ safety and producing also other advantages like energy savings and maintenance scheduling (Figure 1).

SCADRA collects of all the tunnel influence parameters, 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. The data recorded are processed by a specific Dynamic Risk Analysis (DRA) software, which executes a risk assessment in real-time and it defines if the risk is tolerable or if it is necessary to implement further safety measures.

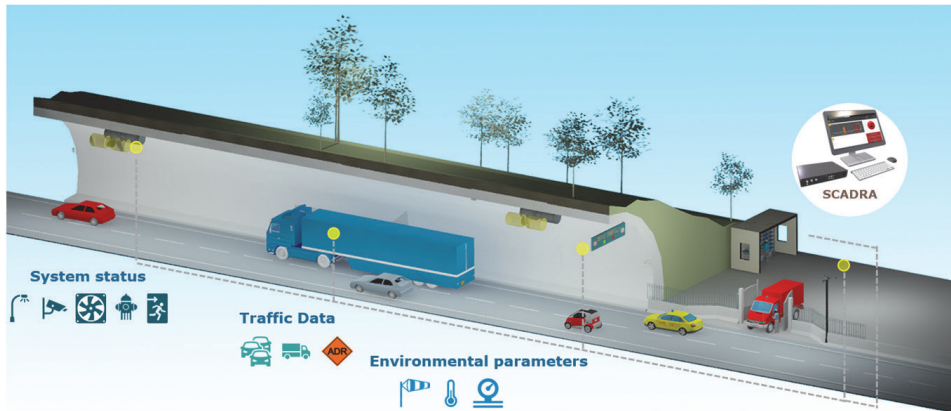


Figure 1 Smart Tunnel with SCADRA

## 4 Artificial Intelligence in the road sector

Artificial Intelligence (AI) and the Generative AI (Gen AI) are concepts and areas of practical application that are quickly growing, in terms of interest, products and services across multiple sectors. The concept is also relevant to the road, transport and mobility sectors in areas such as infrastructure design, operations and management, service provision and meeting the needs of customers. Emerging policies and practices for AI in the roads and transport sector are still novel, emerging and not completely understood. Governments are making efforts around the world to set policies that correctly state the use of AI within the country / region and across sectors. Understanding the potential applications, their potential and actual benefits, challenges and risks is critical to inform and guide future approaches in the road sector. Understanding of this new technology will be key to the success of AI in order to enhance the road sector practices. This item will impact all aspects related to management of road infrastructure including workforce management and traffic management. Public trust and workforce trust will also be key to the success of the deployment of AI in the road sector, especially as a common application of AI will involve controlling the movement of vehicles, e.g., through AI operated traffic signals, connected fleets etc. Other critical AI applications include safety of vulnerable road users and road infrastructure design, construction, inspection, operations, management and maintenance of all road infrastructure assets. Risk analysis with AI offers numerous benefits, including automation of decision-making processes, advanced predictive capabilities, and support for more informed decision-making. This field continues to evolve and offer new opportunities to enhance risk management in different contexts.

### 4.1 Definition of AI in the road sector

Artificial Intelligence and Generative AI (considered as a subset of AI) are the abilities of digital computers, machines or software to perform tasks commonly associated with intelligent beings. The term is frequently applied to the project of developing systems endowed with the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, generalize, or learn from past experience. When applying AI to the road sector, some programs can augment human decisions in performing certain specific tasks, so some activities within the road sector can be performed more efficiently. Particularly, a key benefit of AI is on tasks where machines can enhance humans' capabilities, which often involves repetitive tasks across large amounts of data, for example, objects detection in video, etc. In parallel, AI is also opening new opportunities for new services and management that was not possible previously.

## 5 Risk analysis with AI

Risk analysis with artificial intelligence (AI) is a rapidly growing field that leverages the computational capabilities of AI to assess and manage a wide range of risks across different sectors, as the tunnelling world. AI can support the following fields:

- automation of decision-making processes, as it can automate many aspects of risk analysis by reducing reliance on manual and error-prone procedures, which can improve the efficiency and accuracy of the analysis,
- predictive analysis as it can analyse large amounts of historical data to identify patterns and trends that may indicate potential future risks, enabling taking preventive or corrective measures in advance by using machine learning algorithms,
- data anomaly detection, signalling situations that may pose risks, which is particularly useful in detecting fraudulent activities or abnormal behaviours in real-time,
- management of large volumes of data, allowing for more in-depth and detailed risk analysis,
- risk management, as it can adapt and improve over time through continuous learning, increasing effectiveness in recognizing and managing risks as they acquire more data and experience,
- decision support to risk analysis professionals by presenting relevant information and data-driven recommendations, which helps improve the quality of decisions and reduce the time needed to make informed decisions.

## 6 From dynamic to predictive risk analysis: SCADRA and AI

The goal is to combine the DRA, performed by SCADRA system, with AI, in order to execute a predictive risk analysis by assessing the tunnel risk level trend according to the data gathered and by adjusting the next prediction to the real-time risk data. Thanks to the huge amount of data, collected and analysed by SCADRA installations, it is possible to create a tunnel risk report and program the machine in order to recognise certain parameters combinations that may affect the tunnel safety and to inform and pre-alert the tunnels managers of a possible upcoming critical event. This is likely achievable since SCADRA executes a DRA every 10 to 15 minutes, during the operation period, or in case of sudden changes of traffic or environmental conditions and operating level of safety systems. Therefore, AI can play a significant role in the road tunnel sector, and it can be used to enhance this process by:

- real-time monitoring, since AI-based systems can integrate data from sensors distributed along the tunnel to constantly monitor environmental conditions, vehicular traffic, and other relevant parameters. This data can be analysed in real-time to detect anomalies or imminent risk situations, enabling a rapid response to emergencies,
- traffic prediction and management, as AI algorithms can process large amounts of historical traffic data to predict future traffic patterns within the tunnel. These predictions can be used to optimize traffic management, prevent congestion, and reduce the risk of accidents,
- image recognition and analysis, since computer vision systems can be used to monitor road conditions and identify potential issues such as road blockages, fluid leaks, or smoke inside the tunnel. This information can feed into early warning systems and enable a timely response to incidents,
- sensor data analysis, it can be employed to analyse data from a variety of sensors, including those measuring temperature, humidity, concentration of harmful gases, and other critical parameters inside the tunnel. This analysis can identify early signs of potential structural problems or safety risks,

- decision support systems, by using predictive models and machine learning algorithms, it can assist operators in assessing the risk of various situations within the tunnel and suggest the best corrective or preventive actions to take,
- accident and evacuation simulations, which can be used to model and evaluate potential accident scenarios inside the tunnel and to optimize evacuation strategies in case of emergency.

In summary, AI can significantly improve dynamic risk analysis in road tunnels by providing advanced tools for monitoring, predicting, and responding to risk situations in real-time.

## 7 Future challenges

To integrate artificial intelligence (AI) into dynamic risk analysis of road tunnels, several steps need to be followed.

Firstly, it's important to understand the specific needs and challenges related to risk management in road tunnels (Step 1. Needs and obstacles identification). This may include the need to monitor environmental conditions, predict traffic, detect potential incidents, and respond promptly to emergencies.

Second step is relevant data gathering (Step 2. Data gathering) to train AI models. This can include historical traffic data, environmental data, data from sensors inside the tunnels, and other relevant information. It's important to ensure that the data is accurate, complete, and representative of real-world conditions.

The collected data must be prepared for analysis by AI algorithms (Step 3. Data preparation). This may involve cleaning the data to remove errors or outliers, normalizing the data to make it comparable, and splitting the data into training, validation, and test sets.

There are various AI algorithms that can be used for dynamic risk analysis. These include supervised, unsupervised, and reinforcement learning algorithms, as well as artificial neural networks, decision trees, support vector machines, and others. The choice of algorithm (Step 4. Algorithms definition) will depend on the specific requirements of the problem and the availability of data.

Using the prepared data, AI models can be trained (Step 5. Model training) to perform specific tasks, such as traffic prediction, anomaly detection, or accident simulation. During the training process, it's important to optimize the algorithm parameters and evaluate the model's performance using appropriate metrics.

Once trained, AI models need to be integrated into the existing infrastructure for dynamic risk analysis of road tunnels (Step 6. Model integration into existing infrastructure). This may require the development of dedicated computer systems or integration with existing platforms for traffic monitoring and management.

After deployment, AI models need to be continuously monitored and optimized to ensure they produce accurate and reliable results over time (Step 7. Performance monitoring and optimization). This may include periodically retraining models with fresh data, updating models with new data, and optimizing algorithms to improve performance.

In conclusion, while the AI integration into DRA of road tunnels presents significant advancements in safety and operational efficiency, there remains a need for future studies to address key challenges and further enhance the AI application in tunnel management. Future research efforts should focus on refining AI algorithms to improve the accuracy and reliability of risk analysis, particularly in predicting and responding to emergent situations. Additionally, there is a need for comprehensive studies to assess the scalability and adaptability of AI-driven systems across diverse tunnel infrastructures and environmental conditions.

These studies are crucial for various stakeholders involved in tunnel management, including government agencies, transportation authorities, infrastructure developers, and maintenance personnel. The results of such research efforts will provide valuable insights and tools for optimizing tunnel safety, resilience, and efficiency. Furthermore, the significance of this paper lies in its contribution to the advancement of intelligent transport systems and the broader field of infrastructure management. By elucidating the SCADRA principles and the potential of AI in tunnel risk analysis, this paper offers a roadmap for implementing innovative solutions that can revolutionize tunnel management practices. For transportation authorities and infrastructure developers, the findings of this paper offer actionable insights into connecting AI technologies to enhance the safety and operational effectiveness of tunnel systems. For researchers and academics, it provides a foundation for further exploration into the intersection of AI and infrastructure management.

The importance of this paper extends beyond its immediate audience to encompass all stakeholders invested in the safety and efficiency of transportation infrastructure. Future studies building upon these findings will play a vital role in shaping the future of tunnel management and advancing the broader goals of sustainable and resilient transportation systems.

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